Faculty of Engineering of University of Porto

CLIMATE CHANGES IN BRAZIL: THE USE OF SMART GRIDS AS A MITIGATION AND ADAPTATION STRATEGY

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Abstract

Global climate change is a theme that has been widely discussed and studied in many areas due to its potential impact on natural and human systems. Issues such as vulnerability, adaptation and mitigation has been taken by several sectors, among which the energy sector. In the world, the energy sector is a major contributor for the climatic change phenomenon, although it is also one of the most affected by it, especially the renewable sources. In fact, the energy usage often results in greenhouse gases emissions, affecting climate in such way that deteriorates the potential of renewables generation. As less renewables mean more emissions, this cycle needs to be interrupted.

This thesis is an analysis of the use of smart grid technologies to mitigate and adapt the electrical sector to the climate impacts projected for the coming years. The proposed methodology uses projected impacts of climate and smart grids to predict energy generation and greenhouse gas emissions. This proposal is illustrated by a case study on the Brazilian electric sector that has a particularity of having interconnections between its four subsystems, which allows for the exchange of energy and better utilization of the different hydrological cycles in the country, and already has a large share of renewables.

The results show that smart grids can help to save energy, reduce the operational and maintenance costs and the investments in new power plants after 2030. Smart grid would also help to reduce electricity tariffs, the generation costs and the costs associated with theft and fraud. The best results were achieved for the scenarios that involve the combination of smart grids with the promotion of efficiency and consumers' consciousness in energy issues.

Resumo

As mudanças climáticas globais são um tema muito comentado e estudado por diversas áreas devido a como este evento irá afetar os sistemas naturais e humanos. Questões como vulnerabilidade, adaptação e mitigação vêm sendo levantadas por diversos sectores, dentre eles o setor energético. No mundo, o setor energético é um dos maiores responsáveis pelo fenômeno climático, entretanto, é, também, um dos mais afetados, em especial as fontes renováveis. De fato, o uso de energia geralmente resulta em emissões de gases de efeito estufa, afetando o clima de tal maneira que deteriora o potencial da geração de renováveis. Como menos renováveis significam mais emissões, esse ciclo precisa ser interrompido.

Esta tese apresenta uma análise do uso da tecnologia de redes inteligentes para mitigar e adaptar o setor elétrico aos impactos climáticos projetados para os próximos anos. A metodologia proposta utiliza projeções climáticas e do impacto das redes inteligentes para projetar a geração de energia e emissão de gases de efeito estufa. Tal proposta é ilustrada com um estudo de caso sobre o sector elétrico brasileiro que tem uma particularidade de ter interconexões entre seus quatro subsistemas, que permite o intercâmbio de energia entre as regiões e uma melhor utilização dos diferentes ciclos hidrológicos no país, e já possuir uma grande participação de renováveis.

Os resultados mostram que as smart grids (redes inteligentes) podem ajudar a reduzir o uso de energia, reduzir os custos operacionais e de manutenção e os investimentos em novas usinas a serem construídas após 2030. As smart grids também ajudariam a reduzir as tarifas de eletricidade, os custos de geração e os custos associados ao roubo e à fraude. Os melhores resultados foram alcançados para os cenários que envolvem a combinação de smart grids com a promoção da eficiência e consciência energética.

Contents

Acronyms

A2_SG_S - A2 Smart Grids Slow Scenario

A2_SG_M - A2 Smart Grids Moderate Scenario

A2_SG_F - A2 Smart Grids Fast Scenario

ABRACE – Brazilian Association of Large Industrial Energy Consumers and Free Consumers

Amforp – American Share Foreign Power Company

ANEEL – National Electric Energy Company

AR - Assessment Report

B2_SG_S - B2 Smart Grids Slow Scenario

B2_SG_M - B2 Smart Grids Moderate Scenario

B2_SG_F - B2 Smart Grids Fast Scenario

BEN – National Energy Balance

CA - Current Account Scenario

CC - Climate Change

CCEE - Chamber of Electric Energy commercialization

CCS - Carbon Capture and Storage

CEPED – University Center for Studies and Research on Disasters

CESP - Light and Power Plants of São Paulo

CHESF - São Francisco Hydroelectric Company

CHP - Combined Heat and Power

CNPE - Indicative Planning by the National Energy Policy Council

COP - Conference of the Parties

CTSUL - South Thermoelectric Plant

DR - Demand Response

ECF – European Climate Foundation

Eletrobrás - Brazilian Electric Power Plants SA

EPE – Energy Research Company

ESM - Earth System Models

GDP – Gross Domestic Product

GEE – Energy Economy Group

GHG – Greenhouse Gas

GWP - Global Warming Potential

IBGE – Brazilian Institute of Geography and Statistics

ICT – Information and Communication Technology

IEA – International Energy Agency

IEP - Independent Energy Producers

INPE – National Institute of Space Research
IPCC – International Panel on Climate Change
LEAP- Long-range Energy Alternatives Planning System
LED - Light Emitting Diode
Light - Holding Brazilian Traction, Light and Power Company Ltd.
MAE - Wholesale Energy Market
MME – Ministry of Mines and Energy
MP - Provisional Measure
NGCC - Natural Gas Combined Cycle
OECD - Organization for Economic Cooperation and Development
ONS – National System Operator
OPEC - Organization of the Petroleum Exporting Countries
PBMC - Brazilian Panel on Climate Change
PDE - Decennial Energy Expansion Plan
PNE - National Energy Plan
PU - Public Utilities
RCP - Representative Concentration Pathways
REF - Reference Scenario
REF_A2 Reference A2 Scenario
REF_B2 Reference B2 Scenario
SEEG - Greenhouse Gas Emission and Removal Estimation System
SG – Smart Grid
SG_S - Reference Smart Grid Slow Scenario
SG_M - Reference Smart Grid Moderate Scenario
SG_F - Reference Smart Grid Fast Scenario
SIM - Semi-arid north-east Model
SIN – National Interconnected System
SP - Self-Producers
SRES – Special Report on Emission Scenarios
UHE - Hydroelectric Plant
UNFCCC – United Nations Framework Convention on Climate Change
WG - Working Group
WMO - World Meteorological Organization

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CHAPTER I: INTRODUCTION

Introduction

In 2015, the renewable participation in the Brazilian Energy Sector, according to National Energy Balance (BEN) (EPE/MME 2016), was approximately 41,2%, and about 75,5% in the Electric Sector.

Renewable energy sources are, on the one hand, an alternative to the mitigation of global climate change but, on the other hand, because they are dependent on weather conditions, the resulting production is intermittent or uncertain and, they can potentially suffer the effects of climate change (Schaeffer et al. 2008; Lucena, Schaeffer, and Szklo 2012a).

Furthermore, BEN's reports (EPE/MME 2016) confirm that the renewable energy sources were decreasing its participation in the electricity mix since the end of the 1990's and more strongly since 2011. This is due, especially, to the decrease in hydropower generation (water scarcity) and the necessity to compensate it with an increase in the thermoelectric generation.

The change in the electric mix led to the increase in greenhouse gas (GHG) emissions, which causes higher GHG concentration in the atmosphere potentiates climate changes – extreme events, temperature change, precipitation change and etcetera. So, the vulnerability of the electricity generation in a country, where the production mix depends on the climate, is also expected to increase.

According to Energy Economy Group (GEE) (GEE n.d.), the development of the national energy mix was characterized by a high share of renewable energy sources (hydropower and biomass) in a competitive context but these attributes have been questioned in the last years. The recent energy sector context reveals greater difficulty to merge the attributes of clean and competitive energy and security of supply.

Finally, in what concerns electricity supply, the development of the Brazilian industry has been historically based on two pillars: hydraulic energy efficiency with large reservoirs, coordinated by state-owned enterprises; and the consolidation of this model allowed the electricity supply to become a competitive factor for the Brazilian economy, in terms of price and reliability (Bicalho GEE 2013).

However, the depletion of the most competitive water dams and the restrictions on the construction of new hydroelectric reservoirs imposed a limit to this model. Nevertheless, as the operating rules and planning were maintained, the pillars that supported the previous model are no longer sufficient to meet the reliability and affordability objectives (Bicalho GEE 2013).

Currently, the electric energy system, although based essentially on hydroelectric reservoirs, cannot attend the demand if it only uses the thermoelectric plants in critical moments. This became clear in 2012, when the electricity rationing fears returned to haunt the industry (Bicalho GEE 2013). The Smart Grid (SG) paradigm promises ubiquitous monitoring and control of the entire electric power system, providing optimized management and a deeper exploitation of the infrastructure. The main objective of the present work is to anticipate the potential benefits of SG as an adaptation and mitigation strategy considering the impacts of climate change in the electricity sector.

Motivation

The climate is always changing. However, in the last few decades, human activity has been intensifying this natural process by adding more GHG into the atmosphere. The electricity sector is one of the main responsible for those changes and the renewable generation is seen as a way to mitigate the associated effects. In Brazil, the power sector has been mainly renewable, almost since its creation, but the systems with large share of renewables are more vulnerable to the effects of climate change.

Thus, the hydro generation has been decreasing due to unfavorable hydrological conditions and the thermal generation has been increasing to supply the demand. Therefore, the GHG emissions per MWh produced escalated during the last years.

Smart Grid technologies may help to adapt the power sector to the observed changes and mitigate the emissions caused by the use of non-renewable sources. If smart grid shows itself as able to mitigate the GHG emission in the Brazilian power sector and adapt the sector to the observed effects, it would contribute to reduce the changes in the climate, the amount of gases in the atmosphere and increase the security of supply and the renewable sources participation in power generation. It could also reduce the peak load, the power system exploitation costs and the network losses.

Thus, the following research problem and questions were established to help clarifying the main research goal and identifying the main troubling questions linked to this challenge.

Main Research Question

Can smart grids be used to mitigate the observed climate change and to adapt the power industry in Brazil to the forecasted climate scenarios for 2030?

Auxiliary Questions

How are the Brazilian's power sector generation and consumption situations in 2015?

How demographic and climate variables are expected to evolve in Brazil until 2030?

How is the competitiveness of energy supply in Brazil in the context of restrictions posed by climate change?

How is the status of security of energy supply in Brazil nowadays and how it is expected to be in the next 15 years?

Is it necessary to reduce diversification of electric low carbon emission renewable sources within the new context of climate change and increase the thermoelectric participation in the electric energy mix to guarantee the security of the electric energy supply?

What is the expected impact of smart grids in the power sector in Brazil?

What are the expected impacts of other adaptations and mitigations strategies in the power sector with and without the use of smart grids?

Goals

In order to assess the smart grid's potential to mitigate the GHG emission and adapt the power sector to the expected effects of climate change, the following general and specific goals were defined.

a. General

Estimate the possible contributions of the smart grids to reduce the vulnerability of the power sector to climate change in the projected future scenarios in order to assess its potential as mitigation and adaptation strategy in Brazilian electric energy industry.

b. Specifics

Describe and analyze the Brazilian energy crisis, which is not a recent issue and is not essentially related with climate change, in order to create better forecast scenarios and explore the use of smart grids in other issues related with the electric energy crisis beyond the climate change.

Apply the IPCC's (Intergovernmental Panel on Climate Change) forecast scenarios considering the Brazilian 2030 energy mix, aiming at analyzing the vulnerability of the electric energy supply, considering the planed evolution of the sector, the forecasted evolution of some demographic variables and the evolution scenarios of climate change.

Evaluate how other adaptations and mitigations strategies are expected to affect the power sector with and without the use of smart grids, in order to analyze the synergy between those actions.

Thesis Structure

This thesis is divided into five chapters. The Chapter I presents an introduction for the research, the motivation to start it and the research goals, general and specific.

The Chapter II contains the literature review about the climate change, how it affects the electric system, and how smart grids technology can be used to make the sector more efficient.

Chapter III presents the methodology used to measure the impact of smart grids as a mitigation and adaptation strategy.

The case study for the Brazilian power sector is presented in the Chapter IV.

Finally, Chapter V concludes the thesis and presents recommendations for future work.

CHAPTER II: LITERATURE REVIEW

The climate change impact and the smart grid's effect on the power sector has been the main subject of many researches all over the globe. This chapter aims to contextualize and present the literature review on the state of the art of climate change, power sector vulnerability, mitigation, adaptation and smart grid.

Climate Change

The Earth's climate is always changing as a result of natural processes, e.g., variation in the Earth's orbit, volcanic eruptions and changes in solar radiation. Even if all these processes were constant, variability on climate system (such as drought periods or floods) would still exist. This changeability , between seasons or centuries, is natural, i.e., one can never expect a year or decade equal to the previous one (Marengo et al. 2011). This happen because there is an internally and externally induced climate variability. The externally induced climate variability concerns to variations in the atmosphere, oceans, solar radiation and so forth, "but even without changes in external forcing, the climate may vary naturally, because, in a system of components with very different response times and non-linear interactions, the components are never in equilibrium and are constantly changing" (IPCC. WGI, 2015).

Weather and climate have a profound influence on life on Earth from being a part of the daily experience of human beings to being essential for health, food production and well-being. Based on the relevance of weather and climate on these subjects many scientists consider the prospect of human-induced climate change as a matter of concern (IPCC, 2001).

This work adopts the IPCC definitions of weather, climate, climate change, adaptation and mitigation (Table 1).

Table 1: Main climate related concepts

Term	Description
Weather	"is the fluctuating state of the atmosphere around us, characterized by the temperature, wind, precipitation, clouds and other weather elements. This weather is the result of rapidly developing and decaying weather systems such as mid-latitude low and high-pressure systems with their associated frontal zones, showers and tropical cyclones." (Page 87, IPCC 2001, WGII)
Climate	"in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system." (Page 1760, IPCC 2014, WGII)
Climate Change	"refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcing such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.' The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. (Page 1760, IPCC 2014, WGII)
Mitigation	"Mitigation of climate change is human intervention to reduce the sources or enhance the sinks of greenhouse gases. And Mitigation of disaster risk and disaster is the lessening of the potential adverse impacts of physical hazards (including those that are human-induced) through actions that reduce hazard, exposure, and vulnerability." (Page 1769, IPCC 2014, WGII)
Adaptation	"is the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects." (Page 1758, IPCC 2014, WGII) "Incremental adaptation – adaptation actions where the central aim is to maintain the essence and integrity of a system or process at a given scale." (Page 1758, IPCC 2014, WGII) "Transformational adaptation – adaptation that changes the fundamental attributes of a system in response to climate and its effects." (Page 1758, IPCC 2014, WGII) "Autonomous adaptation – adaptation in response to experienced climate and its effects, without planning explicitly or consciously focused on addressing climate change. Also referred to as spontaneous adaptation." (Page 1759, IPCC 2014, WGII) "Anticipatory adaptation – adaptation that takes place before impacts of climate change are observed. Also referred to as proactive adaptation." (Page 869, IPCC 2007, WGII) "Planned adaptation – adaptation that is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state." (Page 869, IPCC 2007, WGII)

Source: Adapted from IPCC

Furthermore, to work with climate change issues it is necessary to anticipate the most likely future climate scenarios. Adequate climate models are required to make reliable future climate projections, of not only how the average global temperature may increase in the twenty-first century, but also of how these changes can affect climate worldwide (Marengo et al. 2011).

Climate models are described, by the World Meteorological Organization (WMO n.d.), as a mathematical representation of the climate and, "in order to be able to do this, the models divide the earth, ocean and atmosphere into a grid. The values of the predicted variables, such as surface pressure, wind, temperature, humidity and rainfall are calculated at each grid point over time, to predict their future values."

Moreover, according to Marengo et al. (2011), in this grid, the mathematical model makes calculations based on well-established laws of physics that describe the movement of air, changes in atmospheric pressure, temperature and the formation of rain, i.e., the climate and the weather. However, Marengo et al. (2011) emphasizes that it is not possible to represent all the details that exist in the real world, and therefore, certain processes must be included in the model by means of approximations based on expert knowledge.

Additionally, the level of detail of the grid is directly related with the computational time, "the finer the resolution the shorter the interval between each computation" (WMO n.d.) and the complex level of the models used in climate research can "range from simple energy balance models to complex Earth System Models (ESM) requiring state of the art high-performance computing, so, the choice of model depends directly on the scientific question being addressed" (Held, 2005; Collins et al., 2006 *apud* IPCC 2013).

In what concerns the evaluation of the model, according to PBMC (Brazilian Panel on Climate Change) (2014a), climate models are evaluated for their ability to simulate the current climate and the past with respect to average conditions and its variations. If a model can adequately simulate the climate from the twentieth century to the present, then would be expected that future climate projections could be considered plausible (Marengo et al. 2011).

However, the complexity of the climate system makes it very difficult to forecast, particularly in the long term. Some of the reasons for this, according to Marengo et al. (2011), are shown in Table 2.

Table 2: Types of uncertainty

Type of uncertainty	Description
Uncertainty on emissions	It is not possible to predict changes in emissions of greenhouse gases in the future. That depends on various socioeconomic factors, including demographic changes, the composition of energy sources in the future and the course of development.
Greenhouse gas concentrations	Emissions do not match simply the concentrations present in the atmosphere. Carbone dioxide does not undergo chemical reactions in the atmosphere, which means they have relatively long life and is eliminated only by "sinks" of carbon - the oceans and vegetation. Therefore, the projection of future concentrations of greenhouse gases depends of past emissions, as well as of the future, the modelling of flows, carbon “sinks” and how they can change.
Natural variability of weather and climate	The weather system is chaotic by nature, which means it is very sensitive to small changes that cannot be anticipated. The way natural variations develop into a model depends heavily on the initial conditions used in the model; it is not possible to know perfectly. However, as we move into the next century, the exact starting point ceases to be important with respect to climate change caused by increased concentration of greenhouse gases.
Uncertainty of modeling	The knowledge and understanding of the climate system and the ability to model it are limited. Different models - for example, with different grid settings or input parameters - provide different magnitudes and climate change patterns. Likewise, changes in the representation of the modelling process can create different future climate scenarios.

Source: Adapted from Marengo et al. (2011)

Table 2 presented some uncertainties related to climate models and prediction, however, it is important to emphasize that the uncertainty will always be there. It can be exemplified by an observation made by Soito and Freitas (2011, 6).

> “Projections for climate change on a regional level in terms of water resources, that is, predictions related to anomalies in rainfall on drainage basins in Brazilian territory, vary markedly from one model to the other. For example, according to the models from the Hadley Center (England), variations in average surface flow projected for 2050 in the Paraná river basin, assuming an increase of 1% in CO2 concentration, appear as positive in the HadCM3 model (+50 to 150 mm/year in the basin’s margins) and as negative in the HadCM2 (−50 to 150 mm/year in the basin’s margins). The models are more ambiguous in the Southern Hemisphere due to its hydro meteorological observation network being smaller and more recently established than that of the Northern Hemisphere.”

Besides the models, climate change projections also require information about future emissions and concentrations of greenhouse gas, aerosols and other climate drivers. This information is often expressed as a scenario of human activities (IPCC WGI 2013).

The IPCC (2000) define scenarios as “alternative images of how the future might unfold” and say that they “are an appropriate tool with which to analyze how driving forces may influence future emission outcomes and to assess the associated uncertainties." (WMO n.d.)

Thus, the scenarios "assist in climate change analysis, including climate modelling and the assessment of impacts, adaptation, and mitigation" (WMO n.d. and IPCC 2000). However, it is highly improbable that any single emissions path will occur as described in the scenarios (WMO n.d. and IPCC 2000).

The most recent group of scenarios presented by IPCC in the Assessment Report (AR) 5, are known as Representative Concentration Pathways (RCP). "Four RCP were selected and defined by their total radiative forcing (cumulative measure of human emissions of GHGs from all sources expressed in Watts per square meter) pathway and level by 2100. The RCPs were chosen to represent a broad range of climate outcomes, based on a literature review, and are neither forecasts nor policy recommendations" IPCC (2015).

However, the most referred scenarios in the literature are the IPCC ones, namely the AR4 scenarios from 2007, probably because the AR5 scenarios, from 2013, are still very recent. The IPCC's Assessment Reports are defined as "published materials composed of the full scientific and technical assessment of climate change, generally in three volumes, one for each of the Working Groups[1] of the IPCC, together with their Summaries for Policymakers, plus a Synthesis Report" (IPCC, 2015).

The AR4 scenarios, which are explained in more detail in Chapter III, had revealed themselves efficient to predict future climate when comparing historic values with the various IPCC SRES scenarios, as this group of scenarios has been used since 2000.

Moreover, in the literature, the use of the scenarios A2 and B2 of the IPCC to make simulations and projections for local / regional areas, and the use of the baseline period from 1961 to 1990 to compare it with seems as standard.

Furthermore, the use of the scenarios A2 and B2 (and exclusion of scenarios A1 and B1) can be explained by the fact that, according to Bicalho (GEE n.d.), climate changes and

[1]"The IPCC Working Group I (WG I) assesses the physical scientific aspects of the climate system and climate change. The IPCC Working Group II (WG II) assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change, and options for adapting to it. The IPCC Working Group III (WG III) assesses options for mitigating climate change through limiting or preventing greenhouse gas emissions and enhancing activities that remove them from the atmosphere." (IPCC n.d.)

GHG reduction are global problems but the solution is local as it depends on national policies, available resources, technologies, institutions, and other aspects which differ from a country or region to another.

However, this idea is not consensual, as pointed by von Stechow et al. (2015). Mitigation is a global common problem but will not be achieved if climate policies are “formulated at national and even subnational levels, because, there, many of the non-climate objectives are often more salient as policy drivers”. However, “co-benefits of mitigation hold the prospect of helping to achieve some of these other objectives and reducing the short-term costs of climate policies that accrue on the local/national level”.

As presented, the climate is changing as a result of human activity and impacts are expected all over the globe.

Vulnerability to climate change

The impacts resulting from changes in climate are directly connected to the vulnerability to which natural and human systems are exposed (Soito and Freitas 2011). The climate change can be observed in many places and the following list and Figure 1 from IPCC (2015, p 40, 41) presents some of the perceived changes:

- Each of the last three decades has been successively warmer at the Earth’s surface than any preceding decade since 1850. The period from 1983 to 2012 was very likely the warmest 30-year period of the last 800 years in the Northern Hemisphere, where such assessment is possible (high confidence) and likely the warmest 30-year period of the last 1400 years;
- Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010) with only about 1% stored in the atmosphere;
- Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass. Glaciers have continued to shrink almost worldwide (high confidence). Northern Hemisphere spring snow cover has continued to decrease in extent. There is high confidence that there are strong regional differences in the trend in Antarctic sea ice extent, with a very likely increase in total extent;

- Over the period 1901–2010, global mean sea level rose by 0.19 [0.17 to 0.21] m (Figure 1). The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia.

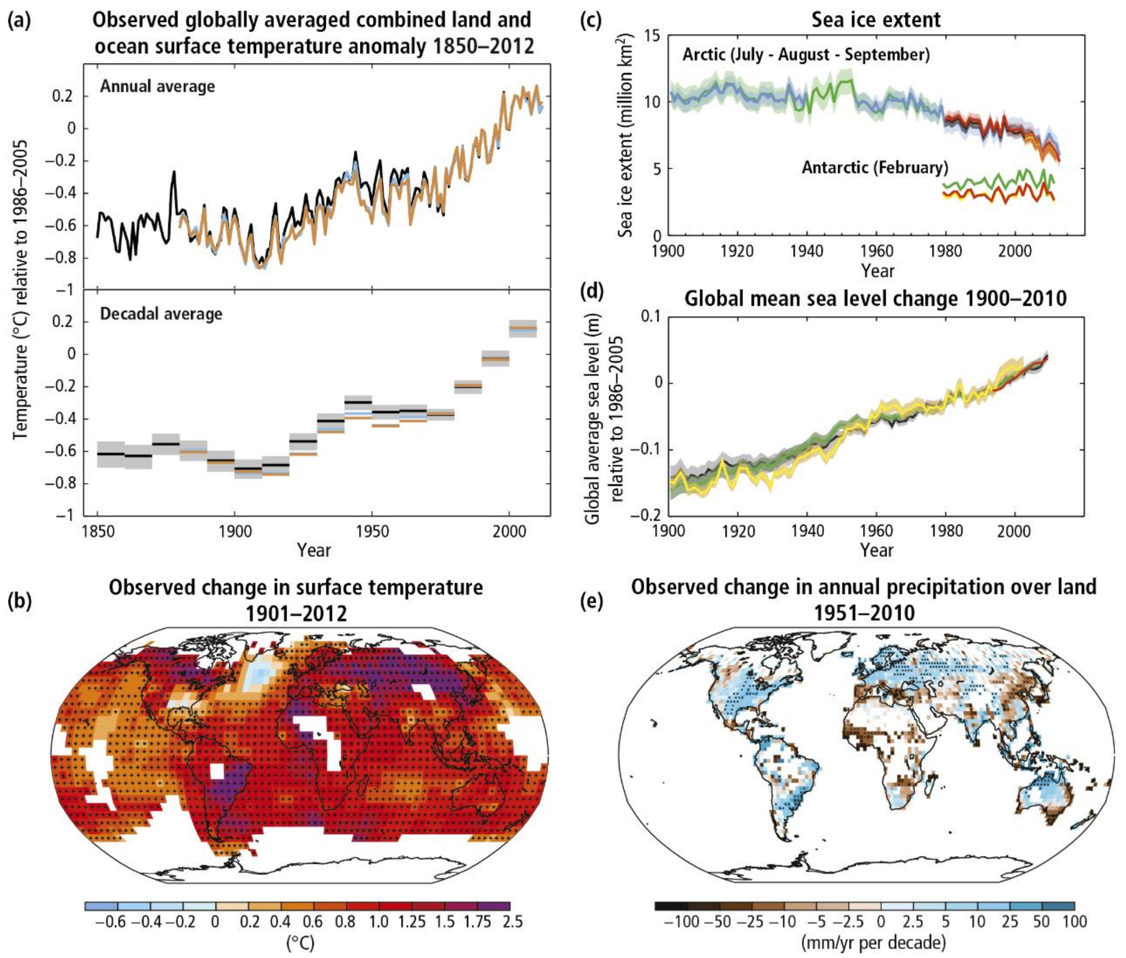

Figure 1: Multiple observed indicators of a changing global climate system
Source: IPCC 2015

As seen above, climate change can affect many sectors - such as health, food production (frost-free season and growing season are expected to lengthen), etc. – and will have an impact on human well-being. One of the main sectors that will be affected by climate change is the energy sector and its vulnerability to this event is addressed in the next topic.

Energy Sector Vulnerability

The literature review presented in this document maintain it is very likely that climate change is due to human activities related to GHG emission. According to the European Climate Foundation (ECF) (2014), in what concerns the energy sector, in general, it will be affected in different ways by climate change:

- Increase in the demand: greater demand for cooling, economic growth and the rising global population;
- Extreme events: disruption and production shutdowns in the oil and gas industry;
- Sea level rising: power plants in coastal areas, oil and gas offshore facilities;
- Storms: will affect electric grids and generation;
- Rise in global temperature: will affect generation, thermal and hydro power stations;
- Weather changes: may affect bioenergy crops.

According to IPCC (2014) “climate change involves complex interconnections and changing likelihoods of diverse impacts” and “susceptibility to climate change differs across sectors and regions” (IPCC, 2001).

The energy industry is considered the biggest contributor to climate change, but it is also the one that will suffer the most with its effects.

The impacts of climate change will not be equally distributed among regions and populations. Individuals, sectors and systems can be affected in different intensities according to geographical location, weather, social, economic and environmental conditions and infra-structure (Soito and Freitas 2011).

According to ECF et al. (2014), “three climate-change phenomena will have a particular impact on the energy sector: global warming, changing regional weather patterns (including hydrological patterns) and an increase in extreme weather events”. However, while most climate change’s impacts are likely to be negative, a few positive effects might also emerge, such as lower energy demand in cold climates (ECF et al. 2014).

The power sector, in particular, will be affected all over the world and, according to McConnach, Zobaa, and Lapp (2011), it is facing challenges to make the transition to renewable and sustainable sources, to grow the use of smart grid’s technology, meet the growing demand, maintaining the service reliable and price competitive, among others.

Renewable energy is more vulnerable, due to its dependence to weather and climate. However, fossil energy supply technologies, though relatively less susceptible to variations in environmental conditions, are not totally free from eventual impacts from climate change (Schaeffer et al. 2012).

So, all energy sources can be affected. Nevertheless, there is a relationship that must be studied with more attention when analyzing the energy sector's vulnerability: the energy and water relationship, which will be discussed in the next topic.

Hydric Crisis

Finally, the last problem to be addressed in this section is the relationship between water and energy and how it would be affected in the future. The current necessity to reduce the energy consumption and the carbon emissions make this relationship a global issue, especially because a huge amount of water is used to produce energy and the energy is also necessary for water supply and water treatment (Anjos, Rocha, and Andrade, 2014).

In addition, water is required for the generation, operation, processing and transport of fossil fuels. It is also used for drilling and fracturing in oil and gas exploration, in cooling systems for power plants, production of electricity in hydroelectric plants and the cultivation of the raw materials used to produce biofuels, which require high amount of water to be obtained (Anjos et al., 2014). i.e., the water is related with the production of almost all the energy transformation forms.

However, the amount of water available is limited. "There are approximately $1{,}386 \times 10^6$ km^3 of water found on Earth; however, 97% is saline, and 99.7% of the freshwater is trapped in ice caps and glaciers, or found in groundwater, which requires energy for removal, leaving 0.1 million km^3 aboveground in lakes, swamps and rivers, and about 13×10^3 km^3 in the atmosphere" (Mcmahon and Prince, 2011).

Furthermore, the "surface water has not increased for the past 20 years, and simultaneously, groundwater tables have been dropping. Currently, 700 million people around the world face water scarcity, and by 2025, that number is expected to increase to 1.8 billion people" (Mcmahon and Prince, 2011).

As the literature points out, the water issue can be very serious, not only for the energy sector. Therefore, because of these and all the previous points addressed, mitigation and adaptations strategies should be a priority, especially for the energy sector, to assure its reliability during the time to come. Thus, the next topic will address such strategies.

Mitigation and adaptation to climate change in electric sector

After addressing all the observed problems, this section will address the mitigation and adaptations efforts to deal with the climate change.

It is well known that the negative effects of climate change can be very damaging for the economy and environment, though, according to Bernauer's (2013) research on climate change policy making, problem solving presents itself as being much harder than many practitioners and scientists initially expected.

The challenge in solving the climate change problem starts with the fact that "climate change mitigation is a global collective good (sometimes also called a global common pool resource) whose 'production' requires global collective action"[2] (Bernauer 2013).

However, as the observed climate change is due to the GHG emissions in the past, it is attributed to the richest and developed countries with large GHG emissions. On the other hand, as pointed by Bernauer (2013) they are likely to suffer least from climatic changes because they have a higher capacity for adaptation.

> "They have an incentive to invest in adaptation measures, rather than in mitigation, because the investing country can directly appropriate the benefits of adaptation. Developing countries, in contrast, are much more likely to suffer from climatic changes because of their smaller capacity for adaptation. Yet, even if they reduced their economic growth to zero, they could not (with the exception of China, India, and Brazil) contribute in a significant way to solving the problem. And those large emerging economies whose commitment to major GHG reductions is essential have a different social rate of time preference (discount rate) than mature industrialized economies: they prefer to grow first and "clean up" later" (Spilker 2012 apud Bernauer 2013)

[2] A similar situation had happened during the 1980s, a global environmental problem with somewhat similar geophysical properties: the depletion of the stratospheric ozone layer. Emissions of ozone-depleting chemicals worldwide had, similar to the climate problem, changed the composition of the atmosphere. In the ozone case, the thinning of the stratospheric ozone layer leads to increased UV radiation, which in turn is detrimental to agricultural production and human health. Within 10 years, an effective global regime was established, and the ozone layer is likely to be back at its preindustrial level within the next few decades. The global ozone regime is based on a framework convention established in 1985, a protocol established in 1987, and a series of amendments to this protocol. However, "in the ozone case, the benefits of solving the problem were very substantial and easy to communicate to the public (e.g., less skin cancer and less damage to agriculture); the overall costs of solving the problem were orders of magnitude smaller (a few billion US dollars, compared to hundreds of billions of dollars or more in the climate case). In the ozone case, the problem was solved through a shift to alternative chemicals. This substitution brought some additional economic benefit to a few large firms accounting for a large share of global production of the relevant chemicals. The substitution costs, which per capita were very low, were imposed on consumers. Consequently, the industry concerned eventually welcomed the proposed solution, and the additional per capita costs to consumers were too small to provoke enough opposition to stop the policy" (Bernauer 2013, 425)

On the other hand, GHG emissions from the developing countries are rising faster than those from other countries, and it would not be possible to stabilize climate change without reducing the growth of these emissions but, the main issue is to mitigate the climate change without reducing the development of those countries (Sathaye and Ravindranath 1998)

According to Sandler and Thompson (2004 and 2006 *apud* Bernauer 2013), the climate problem can be compared with the prisoner's dilemma which, "in the climate case also corresponds to the tragedy-of-the-commons logic, is an impediment to global problem solving, that is, global collective action".

According to Soito and Freitas (2011), adaptation is an important factor in climate change and must be dealt with in two ways: assessment of impacts and vulnerability, as well as the development and implementation of strategies and concrete measures in risk management. However, the way to solve the challenge has some problems Bernauer (2013):

- The reduction of GHG emission is a measure for medium to long term and people tend to ignore damages which will occur in the long term and, also, the benefits of mitigation;
- As it should be a long-term policy, the uncertainties in the government, whose preferences can change over time, can be seen as an obstacle to start such policies – "The political uncertainty problem described here is somewhat similar to the time-inconsistency problem in economic theory"; and
- Cost–benefit distributions within countries must be attractive but, in the climate case, few industries will benefit with this, but the costs are likely to be very high to average companies and consumers, which means "neither industry nor consumers are likely to support strong climate policies".

Solomon and Krishna (2011) emphasized the importance on focusing in the power sector as it has "the potential to save much more energy and reduce more GHG emissions than with end use technologies in buildings and vehicles, since large quantities of waste heat can be recovered in a cost-effective and non-polluting manner".

So, when focusing on the power sector, in the view of Bicalho and Queiroz (2012), to talk about energy policies in the world it is necessary to talk about the trade-off equation between energy security[3] and climate change.

Achieving a truly sustainable energy transition requires progress across multiple dimensions beyond climate change mitigation goals (von Stechow et al. 2015).

Energy security has different meanings for each country accord to its position in the world market; for example, energy security for an exporting country like Russia is different from what would be for emerging countries like China and India.

For other countries, such as Japan, energy security refers to the need to compensate for its drastic shortage of energy resources through diversification, trade and investment (Bicalho and Queiroz 2012). Furthermore, in Europe, the problem of energy security revolves around dependence on natural gas imported from Russia; and in the United States, discussing energy security involves addressing the problem of its supply from a perspective that is not restricted to the use of its own resources but incorporates global resources (Bicalho and Queiroz 2012).

According to Bicalho and Queiroz (2012) Brazilian energy security will not depend on global energy markets, either on the import side or on the export side. The role of Brazil in the energy context brings together elements present in the Russian, Indian and Chinese cases. Like Russia, Brazil presents a base of energy resources that makes the country a candidate for a position of net exporter of energy. On the other hand, like China and India, Brazil is a significant emerging energy market. However, unlike Russia, a significant part of Brazilian energy production must remain in the country itself, and unlike China and India, Brazil has achieved self-sufficiency (Bicalho and Queiroz 2012).

Mitigation actions aim at decreasing the level of climate change by reducing GHG emissions or the presence of these gasses in the atmosphere, which reduce the need for new adaptation actions.

In order to sustain international climate negotiations, the United Nations Framework Convention on Climate Change (UNFCCC) was established in the 1992 Rio Convention,

[3] Energy security here means have access to the energy needed in enough amounts and with a reasonable price and avoiding partial or total, temporary or permanent interruption of the service.

to structure the intergovernmental process of negotiation between countries, with the goal of limiting anthropogenic effect on climate. More than 190[4] States have already signed the Convention and committed to stabilizing concentrations of greenhouse gases in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (Bicalho and Queiroz 2012).

Among the advances in this intergovernmental process can be highlighted (Bicalho and Queiroz 2012):

- The Kyoto Protocol, adopted in 1997 at COP (Conference of the Parties) 3, which set concrete targets for reducing greenhouse gas emissions and mechanisms for nations to achieve this goal;
- GHG emission limit of 5.2% was established in relation to 1990;
- The principle of differentiated responsibility, which recognizes developed countries as being primarily responsible for the current high levels of GHG emissions into the atmosphere, which has been the result of more than 150 years of industrial activity;
- During the COP 15 the long-term goal of limiting the maximum increase in global average temperature to no more than 2 degrees Celsius over pre-industrial levels was subject to a revision in 2015 but, there was no agreement on how to do this in practical terms;
- The COP 16 in Cancun strengthened international recognition on the need to limit global warming to 2 degrees Celsius and to achieve this it was necessary to take practical and concrete measures to reduce GHG emissions and to take advantage of adequate funds for these actions;
- COP 21 in Paris, in 2015, one of the goals is to keep global warming below 2 ° C, further seeking to raise the temperature to 1.5 ° C above pre-industrial levels and that developed countries should invest $100 billion for measures to combat climate change and adaptation in developing countries.

These facts lead to conclude that the world knows the danger of not limiting the climate change effects, particularly the temperature rise. However, no one know for sure how to achieve it effectively considering all the limitations, economic, political, ...

[4] Recently U.S. decided to leave the agreement.

Furthermore, Bicalho and Queiroz (2012) explains the climate change and energy security interconnection, which makes difficult to establish policies to reduce climate change. The striking presence of fossil fuels in both climate change and energy security is at the root of the current convergence between environmental and energy issues. For the first one, fossil fuels are the main cause of climate change. For the second one, fossil fuels play a key role in ensuring the energy supply needed for economic development and social welfare, thanks to a set of attributes (storage, density, availability and control) presented by these fuels which allow their use at extremely favorable levels of scale and cost. This antagonism is what creates the conflict between climate and energy goals.

Thus, energy security and climate change are two themes that are correlated through fossil fuels. To reduce climate change it is necessary to reduce emissions, which means reducing the use of fossil fuels and/or reducing the energy consumption.

Moreover, according to Edenhofer et al. (2013), climate change mitigation is not the only critical argument in favor of renewable energy development policies, there is also (known as co-benefits):

- Greater energy security;
- Green jobs;
- Green growth;
- Reduced local environmental damage;
- Reduced poverty;
- Among others.

So, there are two ways to do the transition and they are presented by Bicalho (2013) as being:

- Transition maintaining the resource base: carbon capture and storage technology and continue to use coal.
- Transition changing the resource base: the challenge is to provide renewable fuels with the same attributes[5] as fossils. Therefore, renewables can come in without making a big impact on the energy system.

[5] The attributes are pointed out as being high availability and high stockpile, large stocks and great control over these fuels means that it is possible to have this energy when it is wanted, where it is wanted and when it is wanted. This is the great quality of fossil fuels, it's the advantage they give to the system.

Now, having this in mind, some mitigation and adaptation researches have been conducted in many countries. One of them was led by Shafiei et al. (2015), in which they studied how adaption to climate change would influence the entire energy system in Iceland, from 2015-2050, and to what extent it would change the overall costs and development potential with the intention of quantifying the economic value of adapting the energy supply sector to climate change. They identify the corresponding development paths and implementation of supply technologies in long-term with focus on the biomass and hydro energy resources, as they assumed the impact of climate change on geothermal, wind and municipal/industrial wastes would be insignificant.

As a result Shafiei et al. (2015) concluded that: total installed capacity of future hydro plants would be 6% higher by 2050 (i.e. 880 GWh/year) if adaptation is implemented in the hydro sector; the cost of new hydro resources is reduced by increasing the hydro run-off (glacial and non-glacial) - around 7% by 2050; reduction in the generation cost and the market price of electricity and biofuels. Thus, the energy supply sector in Iceland could be an example of a mitigation-adaptation win-win case.

Lucena et al. (2010) applied an integrated resource planning approach to calculate least-cost adaptation measures to a set of projected climate impacts on the Brazilian power sector, using the A2 and B2 scenarios. Their results pointed in the direction of an increased installed capacity based, mostly, on natural gas, but also sugarcane bagasse, wind power and coal/nuclear plants, to compensate for a lower reliability of hydroelectric production, amongst other impacts.

Giannakopoulos, Psiloglou, and Lemesios (2016) conducted a research to investigate the climate change impacts, vulnerability and adaptive capacity of the electrical energy sector in Cyprus until 2050. They found out a decrease trend in electrical energy consumption due to warmer conditions between November and April and an increasing trend in electricity consumption is evident as warmer conditions due to warmer periods in summer between May and October.

Borba et al. (2012) estimated the potential for energy-related GHG emission reductions in Brazil and their abatement costs; as a result they found a potential to reduce future energy-related GHG emissions by 27% in 2030. However, in spite of that, the mitigation

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However, when considering the renewable, the energy is available when it rains, when it is windy and when it is sunny, which means, low availability, low control and low energy liquidity (Bicalho 2013).

potential identified in the country was not large enough, in absolute terms, to reduce energy-related GHG emissions below the current level in Brazil by 2030 (which contradicts Solomon and Krishna (2011) who identified the energy sector as having a great potential to save energy and reduce GHG.

Another research was conducted by Solomon and Krishna (2011) who studied the Brazilian transition from petroleum based fuel to ethanol. “When the OPEC (Organization of the Petroleum Exporting Countries) oil shock occurred, Brazil was importing 80% of its petroleum” and “today, Brazil is the world’s largest exporter of ethanol”. They explained that the success of the program was due to three main factors: “multiple government objectives were met by supporting a major ethanol program; widespread stakeholder support coalesced for the program (despite initial opposition from Petrobras and carmakers); and the government’s emphasis on technology innovation” (Lehtonen, 2007; Gee and McMeekin, 2011 apud Solomon and Krishna 2011).

Solomon and Krishna (2011) also provided a list of general lessons, after studying a Brazilian (success - shifted from an oil-based transportation system to one based on sugarcane- ethanol), French (success - shifted from oil-fired electric power to nuclear power) and U.S. (failure - attempted to shift from foreign oil to a mix of domestic energy resources) transitions, which can be summarizes as:

- a stated ambition for an energy transition is not enough;
- energy alternatives have to be nurtured through a combination of research and technology development and deployment policies over a sustained period;
- nationalistic sentiments and centralized power appear to be important for marshalling resources in a sustained way;
- existence of new types of energy companies and jobs can help governments to stay committed and focused; and
- relative costs of new energy technologies also must develop favorably.

Therefore, mitigation and adaptation strategies can be used independently to solve the problem, though the importance of using both together is because they are complementary in solving the problem. “Even if emissions are stopped immediately, temperatures will remain elevated for centuries due to the effect of greenhouse gases from past human emissions already present in the atmosphere. Limiting temperature rise will require substantial and sustained reductions of greenhouse gas emissions" but it will not stop climate change but minimize its effects and reduce the longevity of the phenomenon (ECF et al. 2014).

Thus, to reduce emissions to levels commensurate with the internationally agreed goal of keeping the temperature increase since pre-industrial times below 2°C, the share of low-carbon electricity generation by 2050 will need to triple or quadruple. Use of fossil fuels without carbon capture would virtually disappear by 2100 at the latest. The energy sector would be completely decarbonized, and it is likely that technologies able to withdraw CO2 from the atmosphere would need to be deployed (ECF et al. 2014).

Moreover, the investment in low carbon technologies are pointed by the ECF *et al*. as one alternative to the climate problem. The foundation suggests that

> "replacing existing coal-fired heat and/or power plants by highly efficient natural gas combined cycle (NGCC) power plants or combined heat and power (CHP) plants can reduce near-term emissions (provided that fugitive methane release is controlled) and be a 'bridging technology' to a low-carbon economy. Increased use of CHP plants can reduce emissions. CCS, nuclear power and renewables provide low-carbon electricity, while increasing energy efficiency and reducing final energy demand will reduce the amount of supply-side mitigation needed. In 2012, more than half of the net investment in the electricity sector was in low-carbon technologies" (ECF et al. 2014).

However, supply-side investments required to meet the 2°C target are estimated at USD 190–900 billion per year on average up to 2050. Much of this investment would yield co-benefits such as reduced air and water pollution, which would include human health and well-being, and increased local employment. But supply side mitigation typically also carries risks (ECF et al. 2014).

Based on that, many mitigation strategies were identified for developing nations and they are classified, according to Sathaye and Ravindranath (1998), into two categories: energy efficiency, which reduces the use of energy without compromising the level of service; and switching to less–carbon intensive fuels, which is reducing GHG emission without reducing energy generation.

Thus, to avoid or minimize the effects of climatic changes, some mitigation and adaptation policies have been suggested by some studies by institutions related with climate change and some researchers in the area (Pereira et al. 2010 apud PBMC 2014b;

Lucena, Schaeffer, and Szklo 2012a; Lucena et al. 2009; Sathaye and Ravindranath 1998):

- Demand side:
    - Definition of electricity prices to reflect the actual propensity of customer payment, which would increase the price paid by customers with higher income as the waste of electricity tends to be higher among these users;
    - Granting low-interest loans for conservation programs and replacing equipment by government financial institutions;
    - A discount to customers who switch to more efficient equipment can be an interesting option for utilities when the cost of supply expansion threshold exceeds the cost of discount program;
    - Creating Energy Conservation Companies, which can conduct audits, installing new equipment and implement conservation programs in companies. They can also benefit from energy efficiency auction;
    - The creation of energy efficiency standards even more severe and applied more broadly to a wider range of electrical appliances equipment;
    - Incentives for substitution of electric showers by gas heaters (more economically viable alternative), or even solar panels;
    - In the case of air conditioning and food preservation, it would be interesting to encourage broader replacing inefficient equipment with more efficient models;
    - Use of more efficient lighting, such as high-pressure sodium lamp, mercury vapor or the more modern and more efficient LED;
    - In office buildings and shopping malls, thermal storage systems can be an economically interesting alternative to reduce electricity consumption at times when the rate is higher;
    - The direct implementation of solar panels in low-income communities by their own dealers may be advantageous for companies: as low-income consumers pay lower tariffs, would be more profitable for the dealership selling the energy saved to consumers who pay more. In addition, by reducing electricity bills of low-income consumers, utilities would face less default; and may be easier / cheaper decrease the demand for these communities to reduce the theft of electricity (this measure got attention

after being implemented, during the 1980's, by a Californian company which changed, for free, normal lamps for more efficient ones in municipalities that were classified as bad payers; doing this the company saved energy and concluded that was more interesting to invest in this measure than to invest to attend more consumers);

- Architectural designs that make better use of natural lighting and ventilation.
- Improving the energy performance of equipment such as cook stoves, lamps, electric motors, appliances, boilers, buildings, vehicles;
- Improving the energy performance of processes, particularly in the energy-intensive industries of aluminum, cement, chemicals, fertilizers, iron and steel, and paper;

- Supply side:
  - The easiest way to increase the surplus energy of the ethanol and sugar mills is to improve the backpressure steam turbine Rankine cycle boiler raising the pressure to 82 bar. An intermediate alternative is the use of Steam Turbine extraction / condensation;
  - Possible need for utilities to buy excess energy from sugar mills, avoiding the costs of generation, transmission and distribution with long-term contracts;
  - Incentives for interconnection of power plants to the grid without undue delay or technical requirements without reasonableness;
  - Incentives for research and development of revolutionary technologies such as the gasification of bagasse and combined cycle power generation in sugar mills;
  - Reduction by the government, of the information barriers in the latest technologies (such as the development of demonstration projects) as well as offer long-term loans with attractive interest rates for sugar mills to adopt more efficient technologies;
  - The expansion of wind power generation (however, wind power energy, in some situation may not be economically competitive);
  - The controlled incineration of waste and the further use of the exhaust gas to produce electricity;

- The recovery of biogas (landfill gas) generated by the natural decomposition of organic waste. In addition to the biogas solid waste, can also be used the gas produced by wastewater treatment;
- Improving equipment for power generation;
- Improving transmission and distribution, by reducing the flaring of natural gas, by plugging of pipeline leaks;
- Improving coal distribution;
- Rehabilitation and efficiency improvements for power plants;
- Rehabilitation and upgrading transmission and distribution systems;
- Reducing transmission losses;
- Creating bagasse/ biomass cogeneration/ bioenergy systems;
- Using small hydropower, wind, off-grid solar photovoltaics, fuel cells, solar thermal power generation, and other renewable energy sources.

Many suggestions are mentioned in the literature, although some of them has the potential to reduce GHG and energy consumption more than others.

Additionally, the use of biomass was pointed as an important mitigation option but, its use must be carefully evaluated because of potentially negative consequences that may undermine the original objective like land use changes, deforestation, conflicts between land and water for food production and biofuel productions, etc. (Edenhofer et al. 2013).

Furthermore, a study entitled Energy [R]evolution, claim that the national energy mix could become close to 93% renewable by 2050. The actions would be focused on the elimination of diesel, oil, coal and nuclear power stations and gradual decrease in the share of running on natural gas in extent that would increase the share of renewable sources (PBMC 2014b; Teske et al. 2015).

However, “even though the emissions landscape is changing rapidly, fossil fuels still provide 81.2% of the world’s primary energy supply. In 2014, for the first time in 40 years, global energy-related CO_2 emissions remained stable in spite of continued economic growth, thanks mainly to declining coal consumption in China” (Teske et al. 2015).

The idea of a clean / green energy system, to avoid climate issues, is already out there and there are, by now, some studies analyzing strategies to make it happen. As this research aims to analyze the potential of smart grid technology to mitigate and adapt the power sector, the next topic will address SG technology.

Smart grids

A smart grid is, according to IEA (2011)

> an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users. Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end-users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimizing costs and environmental impacts while maximizing system reliability, resilience and stability.

Smart grid is a much-commented topic by energy sectors, governments and research institutes, although the integration of automatisms (and other "intelligent" devices) has been always a concern of power engineers.

> "There is no clear line between smart and "traditional" power systems, neither in functionality nor in time. The electrical energy system has always contained components that added a bit of "smartness": protection relays that interrupt power flow, energy meters, remotely operated substations, and cascades of power stations that implement ancillary services. Thus, the upcoming smart grid is not really the first attempt to make the power system smart" (Palensky and Kupzog 2013, 203).

Though, Palensky and Kupzog (2013, 202), when writing a review on smart grid evolution, started with the following famous comparison: "although Alexander Graham Bell would not recognize today's telecommunication system, Thomas Edison would be very familiar with today's energy grid", clamming that is more than time to improve and evolve the electric system.

In order to do that came the concept of smart grid and developing a smart grid would allow us to:

- flexibly manage capacities for growing demand;
- accommodate new sources of energy with bidirectional and flexible grids;
- allow new players to participate in new energy markets.

In this way, "the new technology is seen as an additional instrument available to States to achieve targets for promoting competition, increasing the safety of electricity systems and combating climate change" (Clastres 2011).

Furthermore, the smart grid is also pointed as one key concept for reaching the climate goals.

As the goals heavily rely on increasing the share of renewable energy sources and, it is especially the renewable and distributed types of energy sources (wind, solar, small hydro) that require such flexibility (Palensky and Kupzog 2013, 202), smart grids may reduce or even solve the problem between climate change and energy security previously addressed by Bicalho and Queiroz (2012).

As could be predicted, there is no one simple characteristic that differ a smart grid from a non-smart / traditional grid. “First, it is about functionality. A smart grid can host the latest energy products and technologies. This flexibility is based on two design principles: more distributed architecture, i.e., more physical players in the system, flexibly networked by more information and communication technology (ICT), which implements adaptive controls and other smart algorithms.” (Palensky and Kupzog 2013, 202).

However, Palensky and Kupzog enphasize that

> “it is important to understand that we need an entirely smart energy system, not just a smart grid. The grid, i.e., transport and distribution infrastructure, is certainly important and requires dramatic upgrades but so do the end points of the energy system: generation, storage, and demand. Technological upgrades like more efficient or low-emission technologies must be combined with systematic upgrades, for instance, coordinated demand and supply, automatic analytics, and other ICT-based functions. Demand response (DR) is an example of smart coordination of energy resources” (Palensky and Kupzog 2013, 203).

The US Energy Independence and Security Act of 2007 *apud* Palensky and Kupzog (2013) explicitly lists the smart grid properties as follows:

(1) Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid;
(2) Dynamic optimization of grid operations and resources, with full cyber-security.
(3) Deployment and integration of distributed resources and generation, including renewable resources;
(4) Development and incorporation of DR, demand-side resources, and energy-efficiency resources;
(5) Deployment of smart technologies (real time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for

metering, communications concerning grid operations and status, and distribution automation;

(6) Integration of "smart" appliances and consumer devices;

(7) Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air conditioning;

(8) Provision to consumers of timely information and control options;

(9) Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid;

(10) Identification and lowering of unreasonable or unnecessary barriers.

There are also some assumptions, pointed by the working group on smart grids (2010), about smart grids benefits as:

- Reduction of peak: the studies about this subject are not similar. For the European Regulators' Group for Electricity and Gas (2007, *apud* Working Group on Smart Grids, 2010) this reduction is because of better information in the bill; and for Office of Gas and Electricity Markets (2006, *apud* Working Group on Smart Grids, 2010) the reduction in based on the consumer's potential to save energy with hourly rate;
- Reduction of non-technical losses: when compared to electromechanical meter, electronic ones facilitate the detection of fraud, either through alarms or through indicators;
- Reduction of losses: the reduction of the maximum demand of low voltage circuits and total consumption results in a decrease in technical losses because the load of networks and transformer is alleviated;
- Reduction in the total consumption: changing the consumption habits and reducing the non-technical losses.

Moreover, considering the infiltration of smart grids in power systems, a U.S. Department of Energy's report (*apud* Hamilton and Summy 2011) suggests that "100% penetration of smart grid technology in the U.S. could lead to an 18% reduction in carbon dioxide emissions by 2030". And "if the electrical grid were simply 5% more efficient, the efficiency gain could displace the equivalent of 42 coal-fired power plants, and that would equate to permanently eliminating the fuel and greenhouse gas emissions of 53 million cars" (Hamilton and Summy 2011).

Smart grids are also expected to allow reducing the CO2 emission. In the Smart Grids Roadmap by IEA (International Energy Agency) (2011), the best scenario "estimates that smart grids offer the potential to achieve net annual emissions reductions of 0.7 Gt to 2.1 Gt of CO2 by 2050" (IEA 2011, 29). According to this report, these reductions would occur through:

- Feedback on energy usage;
- Lower line losses;
- Accelerated deployment of energy efficiency programs;
- Continuous commissioning of service sector load;
- Energy savings due to peak load management;
- Smart grid support for the wider introduction of electric vehicles;
- Deeper integration of intermittent renewable generation.

Furthermore, to get these emissions reductions values, IEA (2011) analyzed four regions, OECD North America, OECD Europe, OECD Pacific and China, and the data used during the analysis was:

- Annual demand;
- Electric vehicle deployment and peak demand as a function of electric vehicle deployment;
- Demand response potential;
- Future potential electricity uses in buildings;
- Deployment of advanced metering infrastructure.

Smart grid is a concept that is already being implemented in some countries or in a few specific regions of other ones.

Table 3 presents technologies covered by smart grids and reach all the areas of the power sector.

Table 3: Smart grid technology areas

Technologies	Electricity System
Wide-area monitoring and control	Generation, Transmission
Information and communication technology integration	Generation, Transmission, Distribution, Industrial, Service, Residential
Renewable and distributed generation integration	Generation, Transmission, Distribution, Industrial, Service, Residential
Transmission enhancement applications	Transmission
Distribution grid management	Distribution
Advanced metering infrastructure	Distribution, Industrial, Service, Residential
Electric vehicle charging infrastructure	Distribution, Industrial, Service, Residential
Customer-side system	Industrial, Service, Residential

Source: IEA (2011)

Smart grid is shown as a global trend and, according to Palensky and Kupzog (2013), Management and Strategic Studies Center (2012) and Clastres (2011), each country has its particular purpose to implement a smart grid, which can be presented as:

- Europe: motivated by clean energy, reduce GHG emissions, distributed generation and energy efficiency;
  - Denmark and Sweden: possible contribution to widespread use of plug-in electric vehicles;
  - Spain: wants to improve the quality of supply with fewer incidents;
  - Portugal: intends to improve integration of renewables in its electricity system;
  - Italy: reduce fraud;
  - Netherlands: expects to save energy while cutting greenhouse gas emissions;
  - United Kingdom: possibility to boost the availability of dual-energy solutions, leading to economies of scale on the production and installation of meters;
  - France: to inform consumers, control demand for energy, increase the quality of supply, optimize the operation of the energy market, and to limit costs of distribution network operation.
- United States: motivated by network effectiveness and losses; and

- Pacific Asia: motivated by font substitution, demand growth and technological market;

Some researches had been published around smart grid's implementation and its benefits. Xenias et al. (2015) applied a two round Policy Delphi process with a range of sectoral experts who discussed important drivers, barriers, benefits, risks and expected functions of smarter grids, to inform the development of smarter grids. Their analyses indicated broad consensus of the necessity for smarter grids, particularly for economic and environmental reasons; yet stakeholders also associated a range of risks and barriers: lack of investment; disengaged consumers; complexity; and data privacy with measures to make the grid smarter.

IEA (2010b,p.154 apud Clastres 2011) found out that, compared to the baseline scenario in 2050, smart grids offer the potential to:

- Achieve savings of between 0.9 GtCO2 and 2.2 GtCO2 a year;
    - Direct reductions: from 0.2 to 0.85 GtCO2 a year under the Blue Map[6] scenario compared with the baseline scenario;
    - Indirect cuts: from 0.65 to 1.31 GtCO2 a year.

According to the IEA (2011) "peak demand will increase between 2010 and 2050 in all regions" and "smart grids deployment could reduce the projected peak demand growth by 13% to 24%". Moreover, according to Faruqui et al. (2007 *apud* Clastres 2011), automated management can reduce peak demand by 20 to 50%, and overall demand by 10 to 15%, but, "the danger with automated management is that peak consumption may simply shift, reappearing when all the loads reconnect at the same time". However, this possibility is quite reduced under a smart grid environment.

It is important to reduce the peak load as electricity system infrastructure is designed to meet the highest level of demand. So, during non-peak times the system is typically underutilized. Building the system to satisfy occasional peak demand requires

[6] "The BLUE Map scenario is target-oriented: it sets the goal of halving global energy-related CO_2 emissions by 2050 (compared to 2005 levels) and examines the least-cost means of achieving that goal through the deployment of existing and new low-carbon technologies. The BLUE scenarios also enhance energy security (e.g. by reducing dependence on fossil fuels) and bring other benefits that contribute to economic development (e.g. improved health due to lower air pollution)"(IEA 2010).

investments in capacity that would not be needed if the demand curve were flatter (IEA 2011).

Smart grid implementation is expected to increase competitiveness as it is expected to be able to add in U.S. (Hamilton and Summy 2011):

- each US$1 billion invested in smart grid technology is projected to propel US$100 billion in gross domestic product growth;
- greater consumer control over power consumption could add US$5–7 billion annually to the United States by 2015 and US$15–20 billion per year by 2020;
- distributed generation technologies and smart, interactive storage for residential and small commercial applications could potentially add another US$10 billion per year if 10% penetration is achieved by 2020;
- the value creation associated with the smart grid's "green" capabilities can outpace more traditional energy investments. For example, clean-energy investments are estimated to result in 16,7 jobs for every US$1 million in spending, while spending on fossil fuels is estimated to generate 5,3 jobs per US$1 million in spending.

Finally, Table 4 presents some online informative portals about smart grid in some countries and/or regions over the world.

Table 4: Platforms about smart grids projects over the world

Region	Country	Link
North America	United States	http://www.smartgrid.gov/
North America	United States	http://www.nist.gov/smartgrid/
North America	United States	http://energy.gov/science-innovation/electric-power/smart-grid
North America	Mexico	http://vmwl1.iie.org.mx/sitioIIE/sitio/indice.php
North America	Mexico	http://www.cre.gob.mx/inicio.aspx
North America	Canada	http://sgcanada.org/
South America	Colombia	http://www.colombiainteligente.com.co/Pages/default.aspx
Africa	South Africa	http://www.sasgi.org.za/
Asia	South Korea	http://www.smartgrid.or.kr/eng.htm
Asia	Japan	http://arxiv.org/ftp/arxiv/papers/1208/1208.5394.pdf
Europe		http://ses.jrc.ec.europa.eu/
Europe	Portugal	http://www.inovgrid.pt/pt

Europe	Portugal	http://www.inovcity.pt/
Europe		http://ses.jrc.ec.europa.eu/project-maps
Europe		http://www.smartgrids.eu/links
Oceania	Australia	http://www.ausgrid.com.au/

Source: Redes Inteligented Brasil, 2015

The present section presented an overview about smart grids in the world, showing that each country has its own purposes to implement them and remarking that these reasons will influence the kind of technologies that will be applied. This section ends with an identification of the main expected advantages of the smart grids implementations in different countries. The Chapter III contemplates the methodological proposal for this research.

CHAPTER III: METHODOLOGY

This chapter presents a methodological proposal to estimate the impact caused by the implementation of SG as a mitigation and adaptation strategy, considering the effects of climate change in the power energy sector.

To answer the research question, the characterization of the methodological approach is presented in Table 5.

Table 5: Methodological approaches

Point of view	Methodology	Justification
Nature	Applied	Find a solution for an immediate problem facing an economic sector and, consequently society.
Approach	Quantitative	Quantitative measures of the phenomenon characteristics.
Goals	Exploratory	Initial approach in order to become more familiar with the problem.
	Descriptive	Enable the creation of scenarios.
Technical procedures	Bibliographic research	State of the art of the subject
	Case study	Analyse various aspects of the power industry
	Simulation	Construction of potential scenarios to observe the dynamic behaviour of a sub system when imposing/changing some conditions.

Adapted from: Gil (2008) and Marconi and Lakatos (2010)

For the development of scenarios and analysis it was used secondary data, especially from (Operador Nacional do Sistema Elétrico 2015; IBGE n.d.; IPCC n.d.; SEEG n.d.; EPE/MME 2016; EPE - Empresa de Pesquisa Energética 2007; EPE/MME 2015b; Ministério de Minas e Energia 2015b).

The projection of global climate change impacts is not in the scope of this thesis – the climate change scenarios adopted in this work are borrowed from the climate experts (IPCC 2013). The present research is focused on analyzing mitigation and adaptation opportunities to the climatic change impacts on the Brazilian energy sector, and it is based on the studies presented along the literature review. Figure 2 presents a small diagram with the main steps used in this methodology.

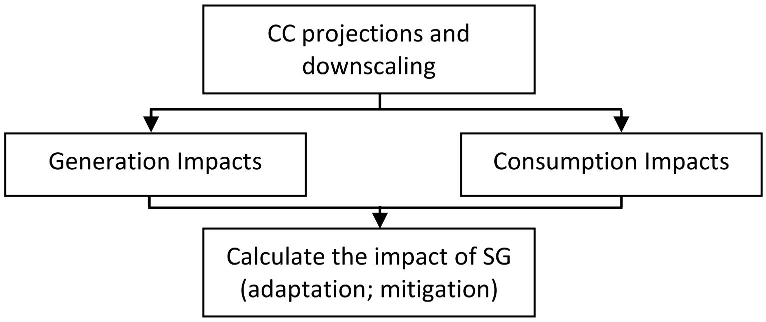

Figure 2: Diagram of methodological approach to analyze the impact of climate change in the power sector and the use of SG as an adaptation and mitigation strategy

The next topic will address in detail each step of the diagram presented in Figure 2.

Methodology to create the scenarios

As this thesis aims to analyze the impact of smart grids in the future Brazilian power grid and discuss its potential to mitigate and adapt the grid to climate change impacts, it is necessary to obtain projections for the future climate, electricity sector and smart grids penetration.

Thus, two alternatives can be considered: (1) construction of new scenarios based on specific indicators present in the literature or; (2) taking on pre-existent scenarios or adaptation of pre-existent scenarios, which were used in previous researches in the area.

As referred before, it was decided to use pre-existing scenarios built by IPCC – SRES family scenarios related with global and regional climate change impacts –, EPE – Brazilian energy sector scenarios for 2030 – and Duarte et.al – Smart Grids penetration and benefits scenarios. Table 5 presents all the different scenarios that will be addressed in the next sub-topics, the pre-existing scenarios for climate change, electric sector and smart grids implementation in Brazil. Each one of the scenarios presented above was created using a specific storyline, which is summarized in Table 6.

Table 6: Scenarios summary

Source	Global Scenarios	Local Scenarios	
IPCC	A1F1	A1F1	A1 Family
	A1T	A1T	
	A1B	A1B	
	A2	A2	A2 Family
	B1	B1	B1 Family
	B2	B2	B2 Family
EPE	Uno World (*Mundo Uno*)	A – In the top of the wave (*Na crista da onda*)	
	Archipelago (*Arquipélago*)	B1 - Surfing small waves (Surfando a marola)	
		B2 - Paddle boat (*Pedalinho*)	
	Island (*Ilha*)	C – Castaway (*Náufrago*)	
Duarte et.al		Conservative	
		Moderate	
		Fast	

Climate Change Scenarios

The SRES scenarios (Special Report on Emissions Scenarios) from IPCC are a group of scenarios created to predict the expected impacts on future climate (IPCC WG III 2000). According to this report, there are four family of scenarios, which are the combination between “A” and “B” with “1” and “2”. The A and B are related with economic and social development and growth being: the "A" families, related with unsustainable and unequal economic growth and the "B" families, relate with the sustainable development and human equity.

In the same way, the 1 and 2 are related to problem solving and integration of the world, being: "1" families, the scenarios that use global cooperation to solve problems and the "2" families, the ones that address/solve problems in a local or regional way.

Figure 3 represents this arrangement.

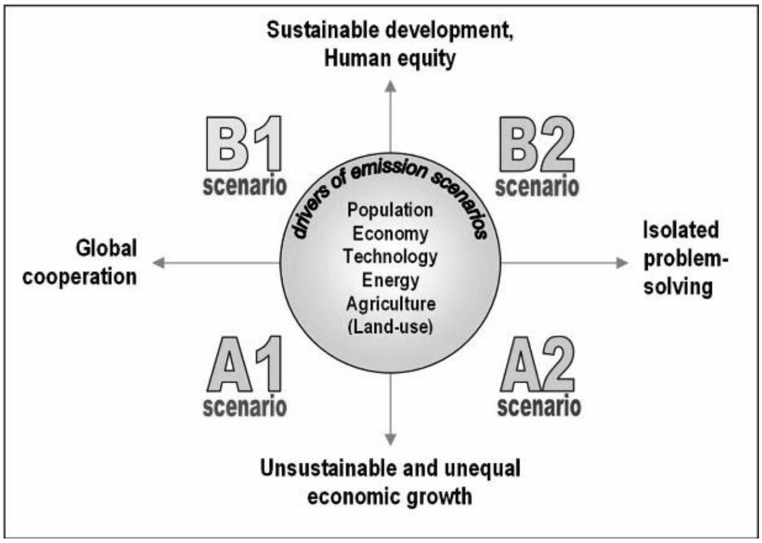

Figure 3: Organization of the family scenarios in terms of problem solving approach
Source: IPCC

Moreover, the storylines for each scenario family is described below.

A1 storyline and scenario family:

- very rapid economic growth
- global population that peaks in mid-century and declines thereafter
- rapid introduction of new and more efficient technologies
- major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions
- substantial reduction in regional differences in per capita income
- A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system
    - A1FI: fossil intensive
    - A1T: non-fossil energy sources
    - A1B: balance across all sources (Balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2 storyline and scenario family:

- very heterogeneous world
- self-reliance and preservation of local identities

- fertility patterns across regions converge very slowly
- continuously increasing global population
- economic development is primarily regionally oriented
- per capita economic growth and technological change are more fragmented and slower than in other storylines.

The B1 storyline and scenario family:

- convergent world
- global population that peaks in mid-century and declines thereafter
- rapid changes in economic structures toward a service and information economy
- reductions in material intensity
- introduction of clean and resource-efficient technologies
- emphasis in global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 storyline and scenario family:

- emphasis is on local solutions to economic, social, and environmental sustainability
- continuously increasing global population at a rate lower than A2
- intermediate levels of economic development
- less rapid and more diverse technological change than in the B1 and A1 storylines
- oriented toward environmental protection and social equity
- focuses on local and regional levels.

The main features of each scenario can be seen in Table 7.

Table 7: SRES driving forces tendencies

	A1F1	A1B	A1T	A2	B1	B2
Population growth	Low	low	low	High	Low	Medium
Economic growth	very high	very high	very high	Medium	High	Medium
Energy use	very high	very high	high	High	High	Medium
Pace of changes in technology	Rapid	rapid	rapid	Slow	Medium	Medium
Technological changes favoring	coal, oil and gas	balance of energy options	non-fossil fuel	varied by region	clean and resource efficient	varied by region
Environmental awareness	Low	low	low	varied by region	High	High
Focus on social equality	Low	low	low	varied by region	High	High
Scale	Global	global	global	local/regional	Global	local/regional

Source: IPCC

Table 7 presented the tendencies for eight driving forces related with climate change.

Lastly, as presented in the literature review and noticed in many studies conducted in the last years, when leading a research on climate change in a country or region, the most used scenarios are the A2 and B2 IPCC family scenarios. Although climate change being a world problem, the policies and the solution will be regional as the resources, access to technology, environmental characteristics, and many other necessary issues that are different from place to place.

Electric Sector Scenarios

Another scenario group are the scenarios for the electric sector, which were created by EPE (Energy Research Agency) in order to develop an expansion plan to the energy sector. The four national scenarios were based in three global scenarios, described below in terms of three critical uncertainties (EPE, 2007) – note that the global scenarios are similar to the SRES scenarios in what concerns problem solve and integration of the world.

- Uno World:
    - Standard globalization:
        - maximum connectivity – multilateralism

    - Power structure political and economic:
        - balance and sharing of political power
        - coordinate macroeconomic policies
    - Conflict resolution:
        - negotiated solutions
- Archipelago:
    - Standard globalization:
        - partial Connectivity – economic blocs
    - Power structure political and economic:
        - hegemony of the blocks led by the United States and European Union
        - recovery of macroeconomic balance in the US economy through internal adjustment
    - Conflict resolution:
        - localized conflicts
- Island:
    - Standard globalization:
        - interrupted connectivity – protectionism
    - Power structure political and economic:
        - greater participation of blocks from Asian countries
        - rupture of China–United States trade relations, followed by slow economic recovery
    - Conflict resolution:
        - sharp differences

These three global uncertainty states were used to create four national scenarios, which will be used during the next steps of this thesis. They can be described as:

- A – In the top of the wave
    - Infrastructure:
        - significant reduction of bottlenecks
    - Inequalities of income:
        - significant reduction
    - Competitiveness of production factors:
        - high earnings and widespread

    - Total economy productivity
        - high
- B1 – Surfing small waves
    - Infrastructure:
        - partially offset bottlenecks
    - Inequalities of income:
        - reduction relevant
    - Competitiveness of production factors:
        - important gains but selective
    - Total economy productivity
        - medium to high
- B2 – Paddle boat
    - Infrastructure:
        - remain major bottlenecks
    - Inequalities of income:
        - small reduction
    - Competitiveness of production factors:
        - little gains significant and concentrated in some sectors
    - Total economy productivity
        - medium for reduced
- C – Castaway
    - Infrastructure:
        - relevant deficiency
    - Inequalities of income:
        - maintenance
    - Competitiveness of production factors:
        - low, although with gains concentrated in some sectors
    - Total economy productivity
        - Reduced

As, used before by Borba et al. (2012), the scenario B1 from PNE 2030 will be used as a baseline/reference scenario as it is the one that better represents the observed evolution. Table 8 presents the evolution of some economic variables in the projections available in the PNE 2030 (EPE 2007).

Table 8: Evolution of economic variables in PNE 2030 scenarios

	A	B1	B2	C
Average Growth Rate of GDP - 2005-2030 period	5,1	4,1	3,2	2,2
Net debt (% of GDP in 2030)	22,5	33,9	55,1	57,4
Investment rate (% of GDP in 2030)	29,5	24,5	21,0	18,7
Balance of trade balance (% of GDP in 2030)	0,3	0,5	1,8	2,2
Balance in current account (% of GDP in 2030)	-2,1	-1,3	-0,8	-0,2
Sector Growth - Average growth rates in 2005-2030 - Agriculture	5,3	4,2	3,5	2,6
Sector Growth - Average growth rates in 2005-2030 – Industry	4,2	3,7	3,0	2,2
Sector Growth - Average growth rates in 2005-2030 – Services	5,1	4,2	3,2	2,2
Sector Growth - Average growth rates in 2005-2030 – Brazil	5,1	4,1	3,2	2,2

Source: PNE 2030 (EPE 2007)

However, Borba et al. (2012), in their study, updated the scenario to better reflect the growth of the petroleum sector activities in Brazil and crude oil prices from PNE 2030 were also altered to reflect the oil price threshold scenario adopted by Petrobras.

Smart Grids Implementation Scenarios

Lastly, one considers the three scenarios (conservative, moderate and fast) proposed by Duarte et al. (2015). Duarte et al. (2015) presented a Brazilian Roadmap, obtained under a R&D project approved by the Brazilian Energy Agency and the Brazilian Association of Distribution Companies. “The SG evolution is represented by the growing penetration of functionalities in clusters along the timeline.” The three scenarios types (slow, moderate and fast) “differ just on the definition of grid evolution parameters, as an increasing curve defined by four parameters”:

- Pi - initial penetration of functionality (obtained from the diagnostic phase);
- Ti – inflection year for increasing rate;
- Tf – inflection year for penetration stabilization;
- Pf – Final penetration of functionality;

Finally, the next topic addresses some issues that needed especial attention during this research.

Attention Areas

Some issues had to be took into consideration during this research. An important caveat here is that the extent of emissions reduction and the corresponding costs in the mitigation scenario are estimated relative to the baseline, whose definition is open to interpretation and judgement about a country's future (Sathaye and Ravindranath 1998).

Several studies reported significant gaps in the availability of infrastructure and climate data, which was perceived during this research.

The hydroelectric expansion presents some challenges, particularly the limit of 72GW as the maximum possible to achieve without violating environmental and social constraints. Although the PNE 2030 aims to expand the hydro installed capacity by 87,7GW in big power plants and 7,0 GW in small power plants, which exceed the previous limitation, bringing some uncertainty related to the execution of the planned expansion.

As Brazil has a power system that is mostly hydro and this source is complemented by others (and not a system that is complemented by hydro) it "must be assessed in terms of a more conservative indicator, such as firm power, to minimize the risk of power shortages" (Schaeffer et al. 2012).

Methodologies to evaluate the use of SG as a mitigation and adaptation option for the energy sector

This research aims to analyze the impact of smart grid in the power sector considering the expected effects of climate change and, in order to do that, some alternative approaches and related concepts are presented.

McDowall & Eames (apud Martinot et al. 2007) offer a typology of energy future studies with two categories, which can be seen in Table 9.

Table 9: Energy future studies

Category	Type	Description
Descriptive	Forecasts	Predict likely futures from current trends, using extrapolation and modeling
	Exploratory scenarios	Emphasize the drivers of possible futures, without specifying a predetermined end state
	Technical scenarios	Explore technology possibilities and configurations, emphasizing the feasibility and implications of different options
Normative	Visions	Elaborate desirable and plausible futures, emphasizing benefits
	Backcasts	Start with a predetermined end point - a desirable (or constrained) future - and then investigate the pathways and technology configurations leading there
	Road maps	Prescribe sequences of policies and measures

Source: McDowall & Eames (apud Martinot et al. 2007)

This phase of the research can be categorized as using descriptive technical scenarios but, also, used descriptive forecasts scenarios as input (information provided during the literature review from previous researches covering similar subjects) for the model.

The climate change studies can also be organized into three categories according to Sathaye and Ravindranath (1998), as:

- Inventory-of-GHG-emissions studies: quantify, for a given year, the level of GHG emissions and sequestration of carbon from all sources in a country;
- Mitigation studies: project future GHG emissions and the economic and other implications of limiting their growth; and
- Vulnerability and adaptation studies: estimate the impacts of climate change on a region or country and evaluate strategies to reduce or adapt to these impacts.

Based on this categorization, this research is a vulnerability and adaptation study.

Besides, in what concerns the model, Shafiei et al. (2015), in their research, used a model divided into four main modules to analyze the energy system in Iceland:

1) Energy supply: capacities and production costs of existing and future plants and calculates the amount of energy that can be available at the various estimated wholesale prices;
2) Energy prices: attempts to equilibrate the demand with the supply curves of various plants by changing the offer prices;
3) Refueling infrastructure: links the energy supply system to transport sector and determines the station service availability as an important factor that conditions the consumer preferences toward alternative fuels; and
4) Energy demand: residential and commercial electricity demands increase in constant ratio to population growth, and the industrial electricity demand is linked to GDP.

Moreover, EPE's (2007) research to plan the expansion of the sector considered six main modules to analyze the energy system, which can be seen in Figures 4 and 5.

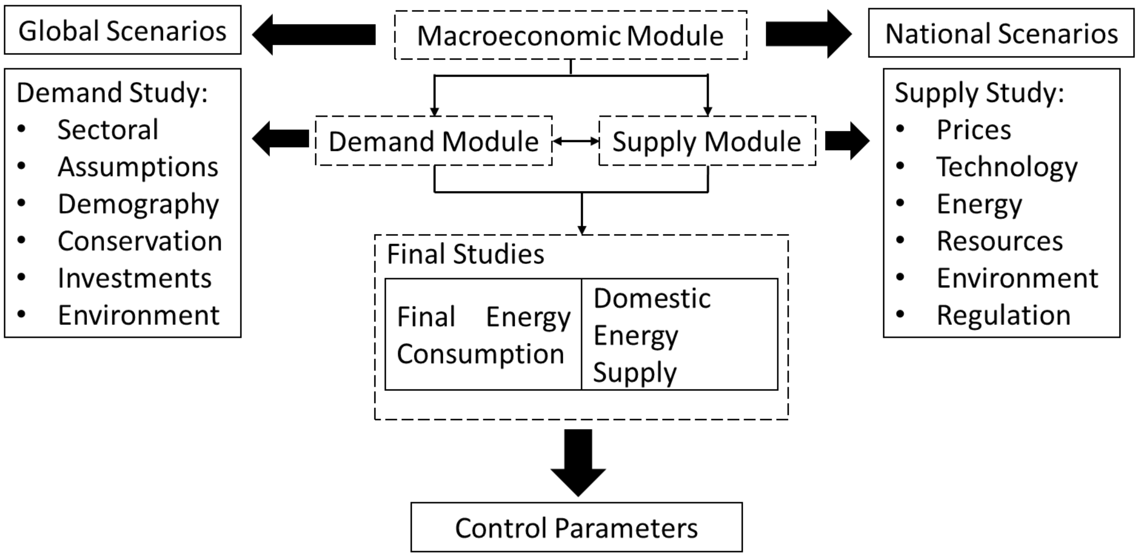

Figure 4: EPE's model construction (a)
Source: EPE (2007)

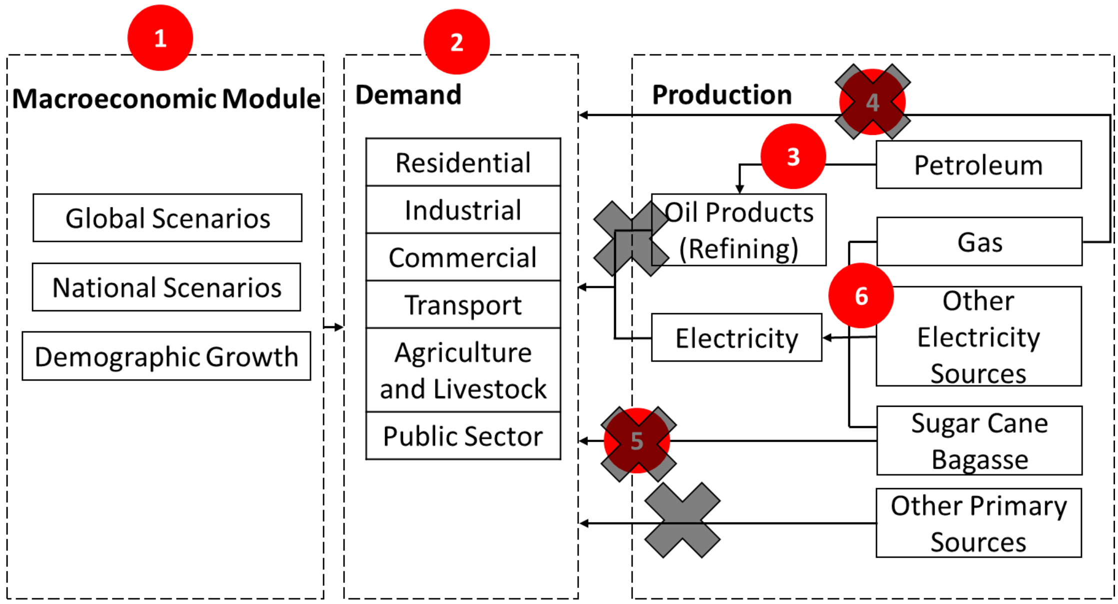

Figure 5: EPE's model construction (b)
Source: EPE (2007)

This research only considers the points 1, 2, 3 and 6 from Figure 5, as the others are not directly related to the electric sector.

Furthermore, Sathaye and Ravindranath (1998) proposed three approaches to evaluate the energy sector mitigation and adaptation options. These are presented in Figure 6 with some emphasis the ones which will be used in this research.

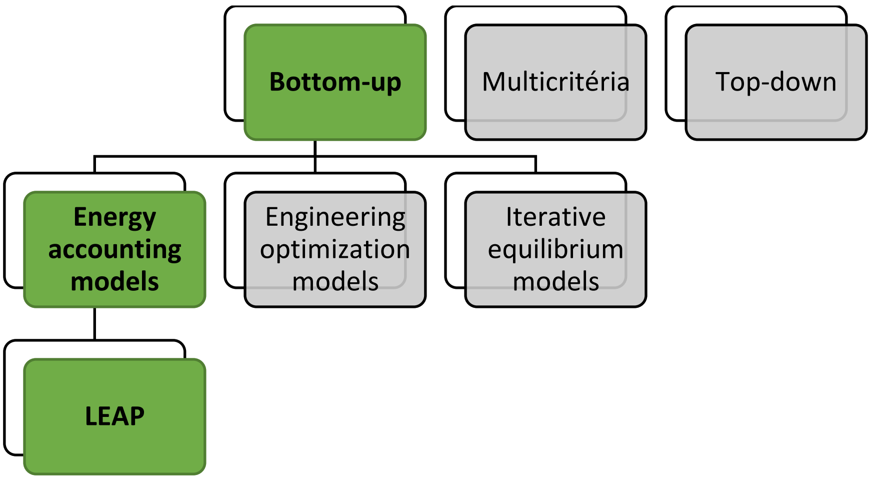

Figure 6: Evaluation approaches
Source: Adapted from Sathaye and Ravindranath (1998)

And they can be described, according to Sathaye and Ravindranath (1998), as:

- Multicriteria: permits the evaluation of mitigation options with respect to both quantifiable and non-quantifiable attributes. These approaches allow an explicit consideration of criteria, such as institutional capacity for implementation, that are difficult to quantify in terms of cost;

- Top-down: analysis of the impact of changes in economic instruments, such as taxes and subsidies, on aggregate economic behavior, which is usually measured by a nation's GDP. The approach explicitly includes feedback between the energy system and the other economic sectors as well as with the macroeconomic performance of the economy;
- Bottom-up: provides a disaggregated picture of energy demand and supply and allows for estimation of potential gains in efficiency from specific technologies and/or the potential for substitution of less–carbon-intensive technologies.

Furthermore, the nature of GHG mitigation assessments varies depending on the GHG producing activity or sector targeted. The bottom-up approach has a characteristic three-step structure (Sathaye and Ravindranath 1998):

1st. Evaluation of GHG reduction and carbon sequestration options:

- Screening options that are to be evaluated and collecting data on their:
    - Technical performance;
    - Energy use;
    - Associated GHG emissions;
    - Costs;
    - Other attributes.

2nd. Development of a baseline scenario:

- Estimating GHG emissions or carbon storage in the target sector for a base year;
- Projecting emissions assuming that current development trends continue, and no actions are undertaken to explicitly reduce GHG emissions;
- Data on the activities that produce GHG emissions or offer opportunities for carbon storage.

3rd. Development of GHG reduction, or mitigation, scenarios, including an estimation of scenario costs and GHG mitigation potential:

- Assess and rank the GHG mitigation options that are appropriate to the country's energy, economic, and social situation according to their potential impact on GHG emissions;

- The efficiency mitigation options may then be ranked in order of their increasing cost per ton of GHG reduced.

For the energy sector, types of bottom-up models include the following (Sathaye and Ravindranath 1998):

(1) Engineering optimization models – linear optimization programs in which the criterion is the total cost of providing economy-wide energy services under different scenarios. The models minimize the cost of providing energy and satisfying end-use demands, ensuring that the amount of energy supplied is at least equal to demand and does not exceed available resource limits.
(2) Iterative equilibrium models – incorporate the dynamics of market processes related to energy via an explicit representation of the balancing of energy supply and demand.
(3) Energy accounting models – basically spreadsheet programs in which energy flows are tracked along with related information such as carbon emissions. The models quantify the effects of mitigation policies, which must then be ranked according to the researcher's judgment.

LEAP, Long-range Energy Alternatives Planning System, according to LEAP and Ennergy Community (n.d.), is a software tool for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute. This tool was chosen to be used during this research due to its (LEAP and Ennergy Community n.d.):

- flexibility as is flexible enough for users with a wide range of expertise: from leading global experts who wish to design polices and demonstrate their benefits to decision makers to trainers who want to build capacity among young analysts who are embarking on the challenge of understanding the complexity of energy systems;
- design, as LEAP is designed around the concept of scenario analysis;
- low initial data requirements. Many modeling tools rely on very particular and often quite complex solution algorithms such optimization, and so tend to have highly inflexible data requirements. Developing the data for such models is a time-consuming task, requiring relatively high levels of expertise; and

- number of built-in tools that make it easy to create complex models and projections.

LEAP is described as “an integrated, scenario-based modeling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. It can be used to account for both energy sector and non-energy sector GHG emission sources and sinks.”

Another approach was developed by Sathaye and Ravindranath (1998), when analyzing the baseline and mitigation scenarios by evaluating the factors contributing to CO2 emissions, used the follow identity:

Equation 1

CO2 emissions = population * GDP per capita[R$/people] * Energy Intensity[TWh/R$] * Carbon Intensity[$CO_2$/TWh]

Note: GDP = Gross Domestic Product

“Bottom-up approaches assume GDP and population growth rates as basic drivers for energy and CO2 emissions growth” and each part of Equation 1 can be described as (Sathaye and Ravindranath 1998):

- Energy intensity provides an indication of a nation’s aggregate energy intensity or the energy needed to support a unit of economic activity;
    - Changes in this indicator may be caused either by structural change in the composition of GDP or by technical energy efficiency improvements;
- Carbon intensity provides information on the carbon intensity of the mix of fuels that supply primary energy;
    - Changes in this indicator may be brought about by a change in the mix of fuels from coal to natural gas or other mitigation options.

According to IEA (2011), the following regional characteristics need to be taken into account in any smart grid regional assessment:

- Current and planned mix of supply, including fossil, nuclear and renewable generation;
- Current and future demand, and sectoral make-up of demand, such as manufacturing industry, residential load prevalence or the deployment of electric vehicles;

- Status of existing and planned new transmission and distribution networks;
- Ability to interconnect with neighboring regions;
- Regulatory and market structure;
- Climatic conditions and resource availability.

Furthermore, “in many cases, modelling of electric energy consumption is multivariate, consisting of a mix of habits, climate and other important economic factors. The main constituents of these economic factors are energy prices, thermal electricity production, share, income, GDP, import and export values and energy demand index." (Giannakopoulos, Psiloglou, and Lemesios 2016).

The projection of global climate change impacts is not in the scope of this thesis. The present research is focused on the climatic change impacts on the Brazilian energy sector, and it is based on the studies presented along the literature review.

Now that the methodology was presented, Chapter IV addresses the case study in the Brazilian Power sector.

CHAPTER IV: IMPACT OF THE CLIMATE CHANGE IN THE POWER GENERATION SUPPLY AND ADAPTATION STRATEGIES: CASE STUDY IN THE BRAZILIAN POWER INDUSTRY

This chapter will present a case study, considering the Brazilian power sector and following the methodology described in the Chapter III. The next section provides a portrait of the evolution of Brazilian power sector in the last years and the main features of the current situation. Follows a presentation of the climatic projections and scenarios and the projected impacts of climate change on the Brazilian power sector. The last sections of this chapter present the expected impacts of SG for mitigating and adapting the sector and, finally, the results discussion.

One of the specific goals of this research is to understand the Brazilian electric energy crisis. This knowledge provided a better ground for the definition of research scenarios and for the investigation of other smart grids applications compatible with climate change mitigation's aim.

Thus, with the purpose of providing a comprehensive portrait of the power sector in Brazil, it is important to know how it has been evolving since its creation, between 1880 and 1900. In order to allow that, this section presents a literature review on Brazilian's power industry depicting its marks, changes and its structure and regulations trough time.

The Evolution of the Brazilian Electric System

Not many years had passed since the 2001 electric crisis in Brazil and the local specialists (Losekann 2015a; Queiroz 2015; Losekann 2015b; GEE n.d.) already talk about a new one.

When analyzing the 2001 electric crisis, Lorenzo (2002) concluded that Brazilian electric crisis is not new for those who have been following and analyzing the evolution of the sector. It started in the end of the 19^{th} century when electricity was introduced in Brazil by small private firms and local governments of small towns which provided power for the illumination of public places and for different types of economic activities. Moreover, different from what is presented today, most of the energy was thermal (Baer and McDonald 1998; Lorenzo 2002).

However, because of the abundance of water and easier access to hydraulic generation technologies, hydroelectricity started to be seen as a more efficient cost-effective alternative, with the use of thermal electricity in situations where the hydraulic potential was presented as modest, complex or costly use (Carneiro 2000).

The initial development was slow (Centro da Memória da Eletricidade no Brasil, 1988; Magalhães, 2000 *apud* Carneiro 2000) but in the beginning of the twentieth century, foreign dealers marked the initial development of the electrical industry in Brazil. The main groups were:

(1) Holding Brazilian Traction, Light and Power Company Ltd., which controlled the production and distribution in the cities of Rio de Janeiro and São Paulo and several small neighboring towns; and
(2) American Share Foreign Power Company (Amforp), a subsidiary of American Bond and Share, which controlled the generation and distribution of electric energy in the upstate of São Paulo, Porto Alegre, Pelotas, Salvador, Recife, Natal, Vitória and upstate of Rio de Janeiro (Feliciano, 1988 *apud* Lorenzo 2002).

> "Soon, after Light entered the São Paulo transportation and electric power market, it overwhelmed smaller local competitors by either absorbing or by eliminating them. In 1904 the Canadian company founded the Rio de Janeiro Tramway, Light and Power Company. In 1905 it acquired a concession, which had been previously granted to a smaller firm, to furnish electricity through the use of hydroelectric power. Soon Light monopolized Rio de Janeiro's power, gas, tramway and telephone system (…) Light dominated the electric power supply in the cities of São Paulo and Rio de Janeiro, other cities were supplied by small locally-owned firms and, by 1920, 343 electric power firms were operating in Brazil on a concessionary basis with municipalities" (Baer and McDonald 1998, 4).

Thus, the oligopoly movement of the system increased during the twenties and led the Canadian Light group and United States company Amforp in a way that, in the transition to the thirties, the major markets and most of the installed generation capacity were already under the control of these two foreign corporations (Carneiro 2000; Baer and McDonald 1998).

Besides, there weren´t relevant institutional barriers to the concentration and centralization of capital. So, foreign groups tended to impose their presence in the industry through aggressive acquisition policies and by merging companies based in the area, a strategy that converged to oligopolistic clusters (Rose et al 1998 *apud* Carneiro 2000).

However, during the 1930s

> “the Federal Government began the institutional changes. All previous arrangements were suspended, including the old ‘gold clause’[7]. Both the precarious conditions of the Brazilian economy as the great world depression spread and also the impact of a nationalistic campaign (…) against the behavior and profits of foreign investors in the public utilities sector led to a decree in July 1934, known as the ‘Código das Águas’ (‘Water Code’)[8], which became the basic legal instrument for the Federal Government to regulate the water and electric energy sectors” (Baer and McDonald 1998, 5).

After that, private groups could “operate only under a concession granted by the Federal Government for the duration of 30 years” and “at the end of this period the assets of the concessionaire would revert to the state”, with or without compensation (Baer and McDonald 1998, 5).

Furthermore, since the 1920s, it became strong, in industrially developed countries, the idea that the Government should compete[9] with private exploration to reduce the price of electricity (Lorenzo 2002).

In what concerns the water code, it came to change the situation in the power sector where companies, especially Light, obtained spectacular profits (Lorenzo 2002).

However, after 1939 with the creation of the National Council of Water and Power, which imposed the review of contracts and concessions, the companies argued that they were discouraged to invest because they were undercapitalized by applying the principle of historical cost, and also because of the prices that were increasing continuously during the late 1930s (Lorenzo 2002).

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[7] The gold clause guaranteed the readjustment of tariffs due to exchange rate variation.

[8] “The Water Code was the first comprehensive legislation on power in Brazil” (Baer and McDonald 1998, 5). It set up a mechanism to supervise firms receiving a concession, ensuring adequate service at "fair" tariffs which would be fixed, taking into account costs, depreciation, and a reasonable rate of return on investments and also would be based on historical cost of capital, and allow a rate of return of 10%. This would be the main reason of discussion in the following years, as Light and Amforp would constantly ask for a rate based on replacement cost (Tendler *apud* BAER and McDonald 1998, 5).

[9] State interventions occurred in Austria, Germany, Switzerland and England, where the Electricity Supply Act, 1926, provides, through the Central Electricity Board, a quasi-socialized system for the regulation of private industries (Lorenzo 2002). According to Guinle (1933 *apud* Lorenzo 2002), between 1910 and 1930 tariffs were lowered in those countries from 100 to 25 (where there were public companies) and from 100 to 50 in the United States, where there was no regulatory laws.

Although, “the principle of tariffs based on historical cost was part of the law, it did not play a role in determining it, due to both, political pressures and to bureaucratic difficulties in implementing it”. But, “from 1937 to 1945, no new concessions were given to foreign companies”, the “government regulation of the sector was delegated to the National Council for Water and Electric Energy until 1960, when this was transferred to a freshly created Ministry of Mines and Energy (MME)” (Baer and McDonald 1998, 5–6).

Moreover, according to Lorenzo (2002), imposing difficulties to import electrical equipment also contributed to the expansion of installed capacity, as helped to develop local industry. In addition, the expansion of demand from the accelerated process of urbanization, the spread of the use of appliances and industrialization, increased uncertainty about the electricity supply in Brazil (Lorenzo 1997 apud Lorenzo 2002).

According to Pereira (1975 *apud* Lorenzo 2002) it created a major impasse where, on the one hand, the government did not have the capital, technology and sufficient management capacity to encompass and expand public electricity services provided by foreign concessionaires. On the other hand, foreign companies could not get the best rates, favored currency regulation and safety for new capital contributions because of the political uncertainties arising from the intensification of nationalist forces.

As pointed by Lorenzo (2002), the most dynamic Brazilian industrial development was between Rio and São Paulo, where also was the big problem on the electricity supply. Light, the dealership in the region since the 1940s, had exhausted the hydroelectric potential, relying instead on expanding the capacity of existing plants and, because of this, there was recurring power outages in the center of the country's economy. In addition to the delay in treatment for new installations and, therefore, featuring pent-up demand situation, there were frequent supply disruptions and sharp drops in voltage, which caused serious obstacles to economic development (Tendler 1968 *apud* Lorenzo 2002).

Besides, “with the decline of investments in the sector during the 1930s and 1940s, Brazil began to experience increasingly severe power shortages, which led to long periods of power rationing” and “given the increasing uncertainty over future returns on investments, both Light and Amforp had little incentive to finance major projects” (Baer and McDonald 1998, 6).

Then, as expected, the Cook mission in Brazil, in the first half of the 1940s, “pointed the electric power sector as being one of the major ‘bottlenecks’ for the country's industrial growth and recommended greater planning and the interconnection of various power systems”. This resulted, in 1946, “in a National Electrification Plan, which emphasized region interconnections” but also requested for “investments to be concentrated in small and medium-sized power plants, with the state acting as coordinator” (Baer and McDonald 1998, 6).

Thus a new strategy began, in 1954, related to division of activities in the sector, leaving the federal and state public enterprises in charge of the expansion of generation capacity and interconnection of the electricity system, while foreign companies - Light and Amforp - would specialize in distribution (Lorenzo 2002).

To help overcome the Southeast supply problems, the Federal Company Furnas Electric Central was built, in 1957, in Grande river, with high-energy use. This plant went into operation in 1963 in the middle of the supply crisis (aggravated by the occurrence of a year of drought when the dam of Billings in Sao Paulo became almost completely empty), and was able to avoid rationing and serious inconvenience to the population and industries (Feliciano, 1988 *apud* Lorenzo 2002).

Finally, the state's presence consolidation in the energy sector took place in 1965 as presented in Table 10, by Baer and McDonald (1998), which represents the transition from private domination in the electricity sector to public domination.

Table 10: Transition from private domination to public domination in the electricity sector in Brazil

	Public		**Private**		**Intra-Firm Supply**		**Total**	
	Power (MW)	**Share (%)**	**Power (MW)**	**Share (%)**	**Power (MW)**	**Share (%)**	**Power (MW)**	**Share (%)**
1952	135.6	6.8	1,635.5	82.4	213.7	10.8	1,984.8	100.0
1955	538.5	17.1	2,248.4	71.4	361.6	11.5	3,148.5	100.0
1958	824.5	20.6	2,742.8	68.7	425.8	10.7	3,993.1	100.0
1960	1,098.9	22.9	3,182.2	66.3	519.0	10.8	4,800.1	100.0
1962	1,791.9	31.3	3,161.4	55.2	775.5	13.5	5,728.8	100.0
1965	4,048.0	54.6	2,486.2	33.6	876.8	11.8	7,411.0	100.0

Source: Panorama, p. 150; Políticas, p. 72. *apud* Baer & McDonald, 1998

The interconnection of electrical systems, as recommended by the Cook mission, became the keynote of the Brazilian electric sector comprising increasingly wide areas and a growing number of dealers resulting into more rational energy production which, consequently, made possible to reduce overall costs, irrigating the country with cheap electricity, resulting in the achieved economic growth (Ibidem, p.53 apud Lorenzo 2002).

However, these expansions occurred under quite problematic conditions and the use of external financing, at a time of unfavorable international situation, brought serious consequences for the evolution of the sector and that was one of the main causes of the crisis that took place during 1970s and 1980s (Lorenzo 2002).

According to Baer and McDonald (1998) and Eletrobrás (2015), since the 1970s the sector was in state's hands and, in the subsequent decades, lots of investments were made to expand generation capacity by building big power plants, interconnecting various state-owned companies and building transmission lines. Besides, the establishment of a cooperation agreement with Germany on a nuclear energy program, which came to minimize concerns about projections pointing a large growth in electricity consumption in the Southeast and the possible exhaustion of the hydroelectric resources of the country until the late 1980s.

From 1974, Brazil tried to maintain its posture and the previous pattern of a forced march towards development (Lorenzo 2002). However, the inflation and external indebtedness process started getting out of the country's control because of the contraction movement of the world economy. With the debt crisis, in 1981-1982, and the disruption of financial flows, Brazil had entered a recession that led to a rapid expansion of domestic debt and, during the 1980s, there was a substantial reduction in the ability of the state to mobilize resources for investment (Lorenzo 2002).

However, according to Baer and McDonald (1998, 8), during the period of state dominance the installed capacity, in the power sector, "expanded from 6,355 MW in 1963 to 42,860 MW in 1984 and 52,741 MW in 1993" though, "most investments in the 1970s were concentrated on power generation, while resources going into transmission and distribution were limited. This created serious sectoral and regional disproportions in the 1980s".

Another asymmetry factor between the different regions in Brazil was related with the tariffs, as stated by Eletrobrás (2015). Therefore, the government, in the end of the 1970s, decided to balance the electricity tariffs in Brazil, creating the Global Guarantee Reserve, which was a new fund that would be administered by Eletrobrás, in order to eliminate differences that were discouraging investment in the North and Northeast, and so, boost regional development. This fund allowed the transfer of Southeast resource companies - mainly from Light and Power Plants of São Paulo (also known as CESP) - to utilities of smaller and poorer markets, which had often incompatible costs (Eletrobrás, 2015).

However, the main aspect of the sector in the end of the 1970s, according to Lorenzo (2002), was its concessionaires financial crisis, when rates experienced constant reductions in their real value, it began a progressive indebtedness process that led to the default and the loss of sectoral efficiency.

In addition, the establishment of the tariff equalization principle to the average interest rate for the sector as a whole, without taking into account the characteristics of each company, aggravated even more the financial framework of the utilities. This happened because any productivity gains that a company would achieve was transferred to another dealer, so that the average rate was kept (Lorenzo 2002). As mentioned by Lorenzo (2002), all these problems generated different types of pressure on the electricity sector, especially with regard to high operating costs and also in the work plans of power companies.

As expected, “during the 1980s the capacity of Brazil's public sector to invest in infrastructure deteriorated progressively. In the power sector, the investments declined from US$ 8.3 billion in 1982 to US$ 3.2 billion in 1993” (Baer and McDonald 1998, 10).

According to Eletrobrás (2015), the worsening of the Brazilian economic crisis in the early 90s, quite affected the electricity sector, starting with systematic delay payment of the energy supplied by federal enterprises and by Itaipu Binational. The debt of these companies came to the equivalent of US$ 5 billion and, in that context, the work program recommended by the Plan 2010 was practically paralyzed, which increased their financial cost at over US$ 1 billion a year (Eletrobrás, 2015).

Furthermore, as said by Lorenzo (2002), the electricity industry entered 1990 in a very delicate situation:

- the state was no longer able to invest in the sector;
- companies found themselves in debt, unable to continue their expansion plans;
- the possibility of a power failure from the beginning of the decade was also a reality.

The resolution of the financial problems of power companies should go through an equity adjustment, and privatization was presented as one of the ideal alternative for this to occur (Lorenzo 2002). So, “the continuing fiscal crisis of the Brazilian state in the mid-1990s led to the decision, by the government, to expand the privatization process of public utilities” (Baer and McDonald 1998, 10).

For Baer and McDonald (1998, 11–12) three important changes were made during the 1990s:

- National System for Electric Energy Transmission was established in 1993: this new institution made possible for any private firm which has energy capacity to have access to the national transmission grid;
- Change in legislation in 1995: eliminated the differentiation between private domestic and foreign firms, and thus allowed the latter to bid for concessions in the electricity sector;
- Creation of a new regulatory agency in 1996: National Electric Energy Agency (ANEEL).

Baer and McDonald (1998, 12) also pointed that “the aim of the government was to create competition among private firms in the generation of electricity and in its distribution, while the transmission lines would remain in the public sector”.

The general trend of Eletrobrás planners in the first two years of this new century was to draft a new expansion of electricity supply, with the participation of the private sector and the increasing use, not only of the country's hydroelectric potential, but also of its thermal sources (Eletrobrás, 2015).

The electricity sector began to include private and public companies, and the operational coordination began to be a responsibility of the National System Operator (ONS) with private nature but created by government initiative, based on the rules of the Coordinated Operation Integrated Group (Lorenzo, 2002).

Wholesale Energy Market, another private nature company, manages the sale of electric energy in the Interconnected System and the state's presence in the sector is predominant, as it controls 78% of generation, 100% of major transformation and 30% of the distribution (Lorenzo, 2002).

Within the federal government, the responsibilities were distributed between the MME and the regulator ANEEL. This decision assignment has not its limits always clear, originating disputes between these entities and private coordinating bodies (Lorenzo, 2002).

Between 1995 and 2004, the Brazilian electric sector changed and, after 2004, the new model of the sector was fully implemented. The differences between the models can be seen in Table 11.

Table 11: Differences between the electric sector's models

Old Model (until 1995)	Free Market Model (1995 to 2003)	New Model (2004)
Financing through public resources	Financing through public and private resources	Financing through public and private resources
Vertical companies	Companies divided by activity: generation, transmission, distribution and commercialization	Companies divided by activity: generation, transmission, distribution, marketing, import and export.
State-owned enterprises	Openness and Emphasis on Enterprise Privatization	Coexistence between State and Private Companies
Monopolies - No competition	Competition in generation and commercialization	Competition in generation and commercialization
Captive Consumers	Free and Captive Consumers	Free and Captive Consumers
Tariffs regulated in all segments	Prices freely negotiated in generation and sale	In the free environment: Prices freely negotiated in generation and sale. In the regulated environment: auction and tender for the lowest tariff
Regulated Market	Free market	Coexistence between Free and Regulated Markets
Determining Planning - Coordinating Group of Electrical Systems Planning (GCPS)	Indicative Planning by the National Energy Policy Council (CNPE)	Planning by the Energy Research Company (EPE)
Hiring: 100% of the Market	Hiring: 85% of the market (up to August 2003) and 95% market (up to Dec. 2004)	Hiring: 100% of the market + reserve
Energy balance surpluses / deficits	Energy balance surpluses / deficits settled in the MAE (Wholesale Energy Market)	Energy balance surpluses / deficits settled at CCEE (Chamber of Electric Energy commercialization). Mechanism of Offset and Deficit Compensation (MCSD) for Distributors.

Source: CCEE 2017

Table 11 presented the old, the transitional and the current models used in the electric sector, from a state owned regulated market to a mix between state and private companies and regulated and free market. It also shows the difference in the amount of energy hired comparing to the marketing, from 100%, to less than the total needed, and back to 100% with an increase of reserve, which raised the security of the system.

Continuing the historical description, more recently, in 2013, to reduce the final price of electricity, it was implemented the provisional measure (MP) 579 which reduce the tariffs and radically changed the way the Brazilian electricity sector was financed.

According to Almeida (2014), the tariff reduction in the electricity sector caused a immediately impact on the financial sector, companies in the electricity sector suffered on the stock market during this year. Even companies that were not directly affected by the MP 579 also suffered therefore, in the stock market because it created an idea in Brazil that it could happen to the other companies, particularly to distribution operators.

The companies started to have difficulties getting financing, as the MP 579 reduced the tariff through the withdrawal of charges and placed on the national treasury the responsibility to make these financings. Several costs are no more at the expense of consumer after the MP 579, like the "light for all" program or the input for generation in the isolated system) (Almeida 2014).

Almeida (2014) points out that the tariff is a recurrent issue in the Brazilian electric sector history that needs a tariff that is sufficient to cover the costs and ensure the expansion of the system. He also states that one of the greatest challenges of the Brazilian electricity sector is how to guarantee cheap energy and reduce the tariffs at the same time. This may be not sustainable as it depends if tariffs revenue will guarantee cost coverage and sector expansion in the long term.

The Brazilian electric sector, historically, has three main energy policy goals, according to Losekann (2013): (1) security of supply; (2) tariff modality; and (3) challenge to increase clean energy into the system. And, the main characteristics of the Brazilian system, which allowed the adequacy of these energy policy objectives (Losekann 2013) can be described as: (1) predominance of hydroelectricity; (2) large reservoirs; and (3) thermal backup of little relevance.

However, according to Losekann (2013), the current situation is difficult to be maintained because of:

- Limited hydroelectric expansion, due to environmental restrictions;
- Less relevant reservoirs, due to environmental restrictions;
- Introduction of intermittent renewables (wind, small hydro, solar, …); and
- Thermoelectric dispatch – the thermoelectric power plants in Brazil were built to be dispatched only during critical times, however, it was being dispatched almost all the time to attend the demand due to reservoirs' low levels.

Besides, Losekann (2015a) declared that there was a crisis in the sector and that crisis has four dimensions:

1) Supply crisis and the new risk of a new electricity rationing in the coming years;
2) Economic downturn, the financial situation is completely disorganized (MP 579);
3) Structural constraints;
    - Main hydropower stations are far from the load centers and doesn't have reservoirs;
    - Difficulty in implementing projects (especially environmental);
    - High risk of new hydroelectric projects delay;
    - Penetration of intermittent renewable sources - bioenergy, solar and wind (pose challenges in the operation of the system)
    - Thermoelectric generating plant not suitable for the Brazilian problem - very expensive thermals were contracted, which are not ideal to be dispatching electricity all the time;
    - Long-term marginal costs of electricity production in the country is increasing (auction A-1 in December 2016 R$ 118,15 / MWh) – Figures 7 to 12, present the evolution of energy prices in auctions in Brazil between 2005 and 2016 (prices in R$/MWh).
4) Difficulty of expansion in the current circumstances (hydroelectric in the Amazon, thermal fuel very expensive, etc.).

In order to complement the information above, Figures 7 to 12 presents the prices of auctions in Brazil between 2005 and 2016 (prices in R$/MWh).

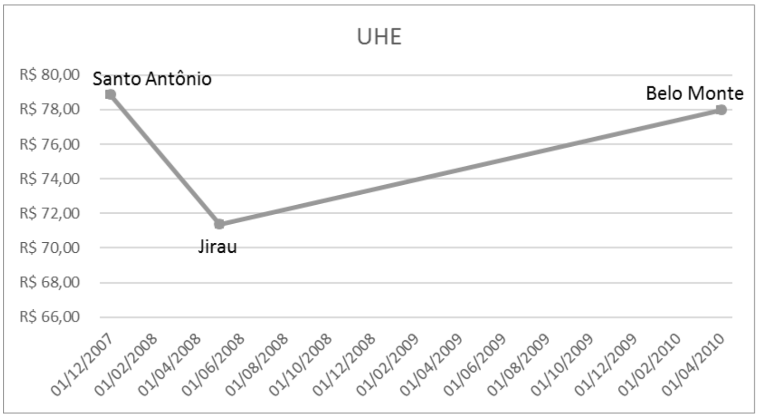


Figure 7: Price of energy acquired in the UHE (Hydroelectric Power Plant with more than 300 MW of installed capacity) auction
Source: Source: Data from CCEE 2017

The UHE (Hydroelectric Plant) does not show any increase as it represents the energy from different new hydro power plants; besides, hydropower from big hydropower plants is the less expensive power source in the country.

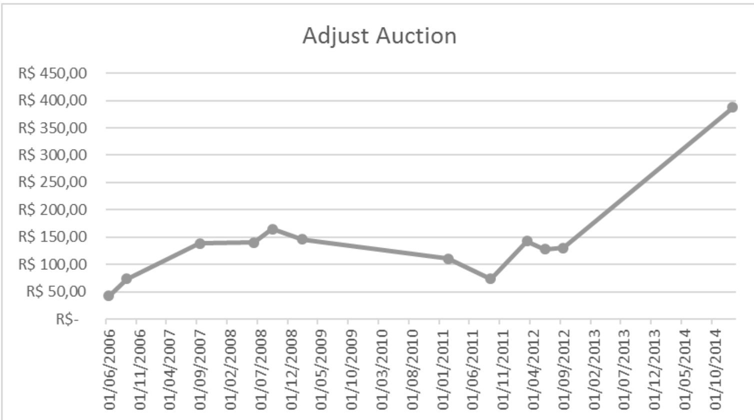


Figure 8: Price of energy acquired in the adjust auction
Source: Data from CCEE 2017

According to CCEE (n.d.), adjustment Auctions aim to complement the energy load necessary to meet the consumer market of the distribution concessionaires, up to a limit of 5% of that load. Figure 8 shows a substantial increase in the prices after November-2011, when the prices increased from R$73,63 to R$397,14.

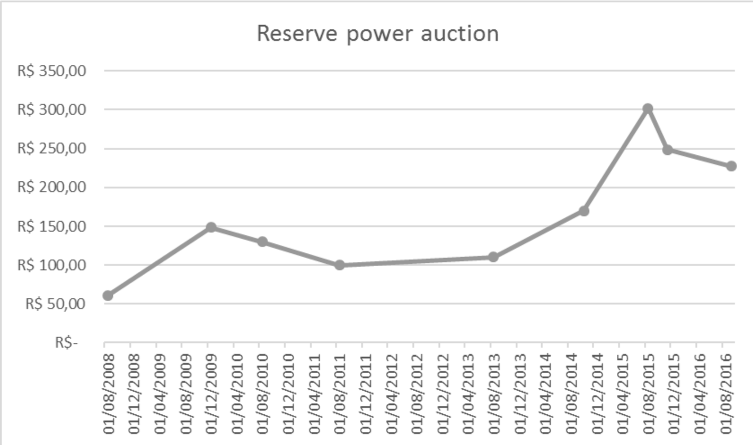


Figure 9: Price of energy acquired in the reserve power auction
Source: Data from CCEE 2017

The reserve energy is intended to increase security of supply in the National Interconnected System (SIN). The prices for reserve energy are increasing too, with a small drop after December-2015.

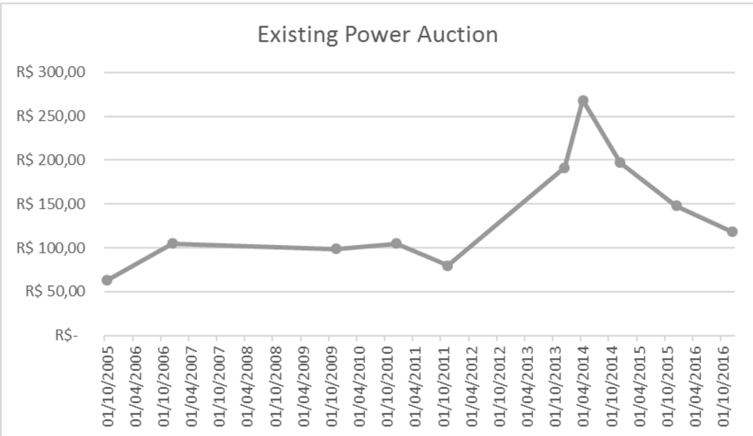


Figure 10: Price of energy acquired in the existing power auction
Source: Data from CCEE 2017

Figure 10 presented the selling prices in the electricity auctions from existing facilities. The prices experienced a fast increase between November-2011 and April-2014 (rapid increase due to change in auctions from big power plants generation to small power plants, natural gas and biomass). However, after that, it started to decrease again (less expensive natural gas).

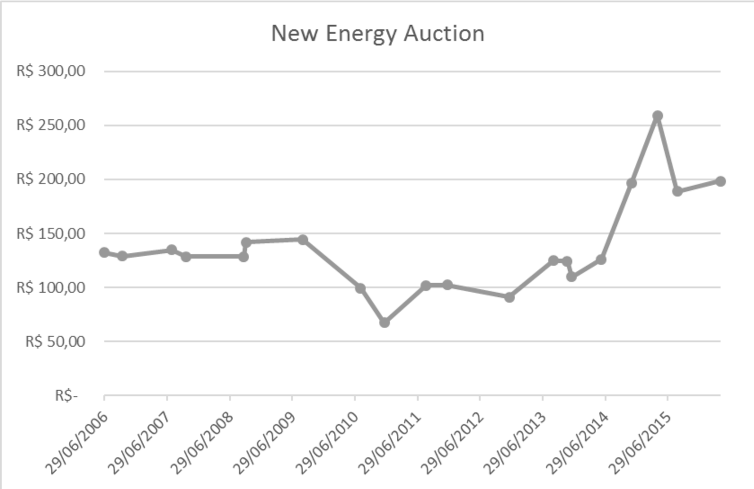


Figure 11: Price of energy acquired in the new energy auction
Source: Data from CCEE 2017

Figure 11 is related to the auctions for the purchase of electric energy from new generation projects, which also experienced an increase during 2014

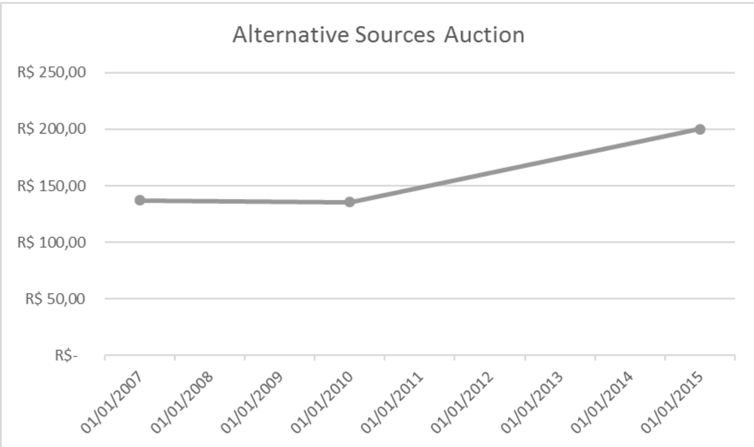
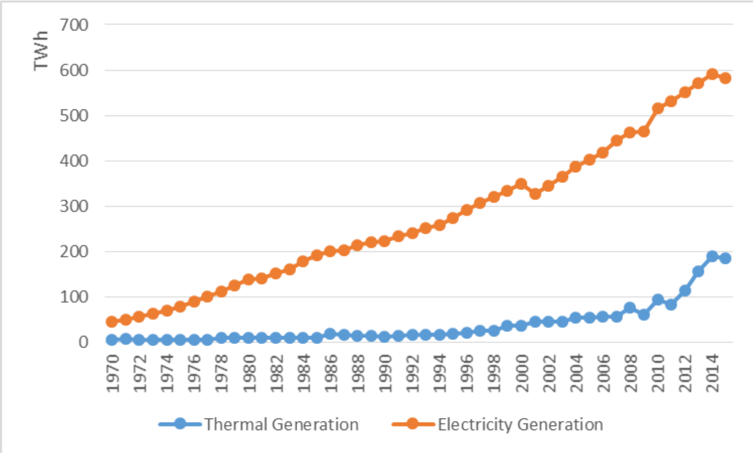


Figure 12: Price of energy acquired in the Alternative sources auction
Source: Data from CCEE 2017

Finally, the alternative sources also got more expensive when comparing the first and second with the third auction.

As shown in Figures 7 to 12, the prices of electricity showed an increasing tendency, even considering the auction, which was introduced in the new model to guarantee the lowest tariff for the captive consumers.

As mentioned before, the participation of thermal generation in Brazil has been increasing and Figure 13 presents the thermal source participation in the electric mix between 1970 and 2015 and Figure 14 presents the sales price (R$/MWh) in the auctions for thermal generation (renewable and non-renewable sources) between 2011 and 2016.



Notes: Thermal Generation includes renewable and non-renewable sources and exclude thermonuclear generation; the generation corresponds to the combination of public and self-producers power plants

Figure 13: Evolution of Thermal Generation in Brazil
Source: Ministério de Minas e Energia 2015a

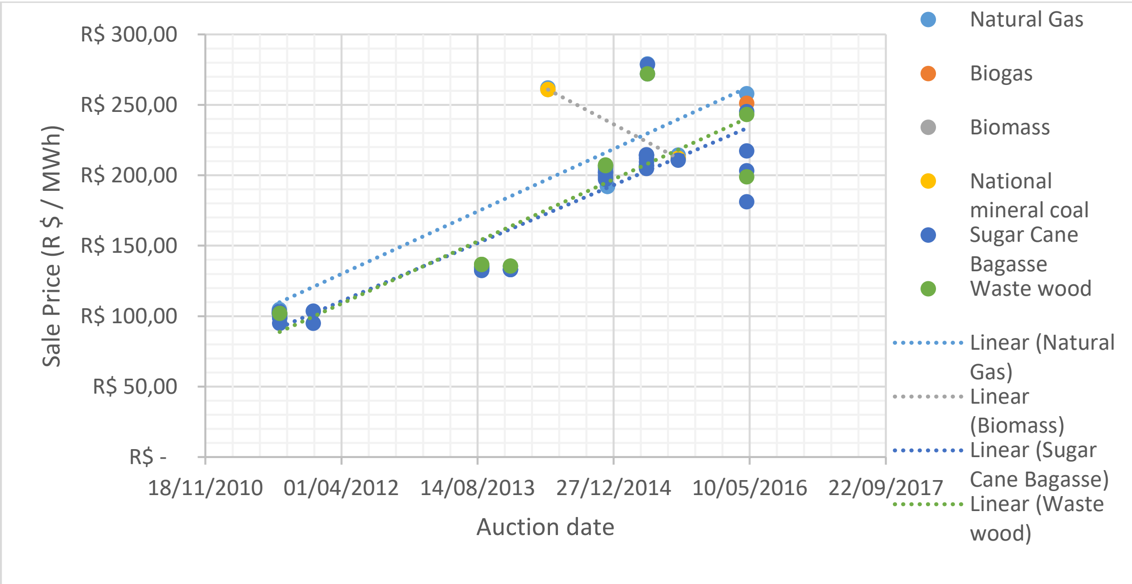


Figure 14: Price that energy was acquired in the Alternative sources auction
Source: Data from CCEE 2017

As presented in Figures 13 and 14, the participation of thermals in the load is growing fast and the costs of thermal are very high (even natural gas) then, this raises the price of electric energy to a value that is not acceptable to the consumer.

Nowadays there are some controversial opinions related to the sector's next steps. According to ABRACE (Brazilian Association of Large Industrial Energy Consumers and Free Consumers) (2013), the world looks at energy, especially the United States and Europe, under two perspectives:

- Energy policies: the strategic security perspective with the United States avoiding relying on Middle Eastern oil and Europe somewhat vulnerable to Russia's gas supply); and
- Climate Change: where they need to clean the energy matrix eliminating or reducing the use of fossil fuels.

Based on these two perspectives, ABRACE (2013) made the following comparison: in Brazil, there is another reality, the country has renewable energy in great quantity and should be not looking at what other countries are doing and following in their steps because the Brazilian's problem is competitiveness. Brazil is already at a renewable use level that is far ahead Europe and U.S. So, ABRACE questioned why not focus on what is interesting for the nation: competitiveness to have development, employment, equalize the trade balance and investment in the country.

On the other hand, for Dutra (2015), the situation presented by ABRACE (2013) is changing, the country was living in a very unique condition with great capacity and large reservoirs, but now, with the crisis of the reservoirs, the increase of the thermals, the increase of intermittent renewable sources; all of that is bringing Brazil closer to the other countries.

Moreover, according to Zanfelice (2015), the problem still has another side, Brazil is one of the countries that have the best resources in the world, great winds and, maybe, one of the best insolation conditions, it has great hydroelectric plants and still producing electricity with such expensive tariffs.

Furthermore, for Queiroz (2015), the model of the electric sector in Brazil is exhausted, the country is experiencing a structural crisis that goes beyond the issue of lack or not of water. On the one hand, there is an institutional model that is already exhausted and on the other hand a group of state-owned companies that are practically broken from the MP 579.

In spite of this, for Zanfelice (2015), it was not the MP 579 that caused the problem which Brazil is experiencing, what it did was to drain all available financial resources that the electricity sector had at hand and, also states that, to get out of the problems the sector needs:

- Generate fund;

- Better define the institutions limits as they do not know what their role really are;
- Create an energy policy – to Zanfelice (2015), maybe the power sector has had an energy policy in the past but it doesn't have one for a long time - today it puts any cheaper source that exists; this is not energetic policy, this is ideology.

Finally, Losekann (2015b) divided the nowadays crisis in three phases as being:

- First phase: scarcity crisis where the basic concern was about the supply and the risk of rationing (peak at the end of 2014);
- Second phase: disruption of the sector's finances. The government focused on actions driven by the equalization of the distributors' situation and reduction of the price;
- Third phase: the currently one, judicial phase. Legal dispute over the losses of the hydroelectric generators, which have to acquire energy in the short-term market with higher prices to meet their contracts since the water to generation has been reducing since 2012 (only in 2015 this loss was estimated at around R$12 billion). The generators' owners understand that they should not bear the totality of these losses because the decisions that resulted in the emptying of the reservoirs and in the hydroelectric generation crisis are decisions made by the ONS and not business decisions.

As noted during the current literature review and emphasized by Lorenzo (2002) the crisis in the electricity sector is not new. The previous and currently problems in the power sector were driven by administration decisions, lack of investment, depletion of water resources and difficulty in meeting the growing demand common in a developing country.

Therefore, it is also important that the proposed solution could help making better decisions, enhance the sector ability to assure security even with lack of investments and water deficit.

The historical data related to the evolution of the electricity sector in Brazil can be found in the Appendix B.

More information on the evolution of the Brazilian Power Industry can be found in (Centro da Memória da Eletricidade no Brasil 2015; Lorenzo 2002; Baer and McDonald 1998; Grupo de Economia da Energia).

Climate Change in Brazil

Some studies approaching climate change have being done in Brazil during the last years. In what concerns the expected effects in Brazil, Perazzoli, Pinheiro, and Kaufmann, (2013) use IPCC climate scenarios A2 and B2 to simulate basin behavior over the period 2071–2100 and compared it with that in the baseline period (1961–1990). They found out a "reduction in river flow of 39.2% and 41.2%, respectively" and that "flood peaks could reach more extreme values in the future, especially under scenario A2".

Besides, "rainfall and evapotranspiration are the most affected, and such changes may affect water availability and sediment production, as well as modifying the hydrological regime and river basin response" as "for both A2 and B2 scenarios, values are lower than for baseline conditions" (Perazzoli, Pinheiro, and Kaufmann 2013).

Hirata and Conicelli (2012), studyed the expected impact of long-term climate change on Brazilian aquifers by 2050. They concluded that climate change will lead to a 70% reduction in recharge in aquifers in the Northeast region (compared to 2010 values), ranging from 30% to 70% in the North. South and Southeast regions are expected to increase in relative recharge values of 30% to 100%. The demand is expected to increase, and the availability of surface water will decrease making the population turn to aquifers as their main source of water for public or private use in many regions of the country.

Another climate change research in Brazil was conducted by Krol et al. (2006) in the Northeast region using integrated simulations, where the model analyzed the region sensitivity to climate change, on scoping pathways of regional development and assessing policy interventions related to dam construction and agricultural alternatives. They found out that those changes could impact water availability in a significant level that should be considered in long-term water policies.

When assessing the effects of market-based mechanisms and carbon emission restrictions on the Brazilian energy system under different scenarios for carbon taxes and abatement targets up to 2050, Lucena et al. (2015) found out an increase in emission in the baseline scenario due to higher penetration of natural gas and coal. However, climate policy scenarios indicated that while taxes up to 32 US$/tCO2e do not significantly reduce emissions, higher taxes (from 50 US$/tCO2e in 2020 to 162US$/tCO2e in 2050) induce average emission reductions around 60% when compared to the baseline.

Salvo et al. (2015), when studying the ecological footprint of many sectors in Brazil, found out that the biggest chunk of Brazil's ecological footprint is due to its carbon footprint and, in particular, emissions from cattle. Only a few economic sectors exhibit high ecological footprint values, chiefly those belonging to livestock farming and energy production based on fossil fuels. Export-oriented sectors have below-average ecological footprint values (excluding the soybeans and slaughter sectors). The percentage of Brazil's ecological footprint due to household consumption (excluding imports) is three times bigger than that attributable to exports, with sectors belonging to livestock farming contributing the most to such disparity. So, the authors concluded that the environmental impact of the Brazilian economy could be drastically reduced by tackling the emission-intensive production processes of a few sectors only and by disincentivize the domestic consumption of a narrow range of products, especially from the livestock segment.

Carvalho et al. (2015), simulated the impact of climate change on potential sugarcane yield in Goiana and Itambé, Zona da Mata of Pernambuco. They inferred that Zona da Mata region can be strongly affected by climate changes, reflecting on a future climate with increased temperature (maximum and minimum) and reduced rainfall, which could reduce the potential sugarcane yield, and that could already be perceived in the near future (2014 e 2040).

Furthermore, Pereira et al. (2013) when refining the analysis of the impacts of the global climatic changes in the wind energy potentials in Brazil concluded that the Eta-HadCM3 model forecasts for future climate scenario A1B indicate a tendency for an average of 15% e 30% growth in the wind power density inland for most of the Northeast region of Brazil, with some regional intensification of more than 100% mainly in the north sector of this region. A decreasing trend in wind power density is expected for the future climate, particularly along the coast of Bahia state. The South region of Brazil exhibited a mild growing trend for wind power density as compared to the Northeast region, about 10%, peaking to more than 20% in some areas. Therefore, it is possible to expect that the overall impact of the global climate changes on the wind power in the Northeast and South regions of Brazil might be favourable to the profitability of existing and future wind projects in both regions.

Complementarily, Lucena et al. (2010) also researched the possible impacts of global climate change on the wind power potential of Brazil. Despite using different models and scenarios from Pereira et al. (2013) (HadCM3 general circulation model and A2 and B2 scenarios), they arrived to the same conclusion: wind power potential in Brazil would not be jeopardized in the future due to possible new climate conditions; improved wind conditions are expected, particularly in the Northeast coast of the country; and investments in wind power generation can be an interesting way to expand renewable energy production in Brazil.

Krol et al. (2001) tried to understand how climate, water resources, agriculture and society influence each other and evaluate the Semi-arid north-east (SIM) model. Their study concluded that a regional integrated model showed itself a suitable tool for complex and interdisciplinary studies. SIM showed a successful integration of models over the complete causal chain climate - water availability - agriculture - socio-economic impacts; the model offers an effective integrated framework for model design and testing. It has the potential to perform scenario analyzes, including studies of regional impacts of global change, but also of the effectiveness of regional policies on water management and land use, as responses to climate variability and possible global change.

Moreover, Schaeffer et al. (2009) analyzed the possible effects of climate change on energy supply and demand in the Brazil, using the A2 and B2 scenarios and the PNE 2030 projections. They concluded that Brazilian society should not only invest on renewable energy but also in studies to use them properly.The Brazilian energy system is vulnerable to climate change as all simulations for different sources, except the sugarcane, show a downward trend in energy supply to a greater or lesser extent, depending on the region. Brazil's vulnerability is as intense as its reliance on renewable energy sources, mainly hydroelectricity and the Northeast will be the most affected region, both in the production of hydroelectric power, due to the reduction of flows in the São Francisco river basin, as in the production of biodiesel and wind energy. Some cultures of oil, such as castor beans and soybeans, may become unviable with the temperature rises and drought projected for the region, and the lowest wind speeds planned for inside northeastern can cause a reduction of up to 60% in potential national wind.

Andrade et al. (2012) conducted a research aiming to identify how global climate change could affect hydroelectric power companies’ internal and external factors, and how they could include responses to potential social, economic and operational performance risks in their strategic planning. The study considered the Northeast region, used the A2 and

B2 scenarios up to 2050 and, as a result, they found out that the main electric company in the region, CHESF, would require the investment in innovative technologies to adapt to the impacts that climate change could have on water resources; could also adapt by using the energy potential of wind, sun, ocean waves and tidal; and by improving efficiency.

Another study was performed by Arroyo (2012), who analyzed the impacts of climate change in the mineral coal thermal power plant in Brazil through a case study in the CTSUL (South Thermoelectric Plant) power plant. The main conclusions were that: the availability of water would not represent a problem to the power plant as the amount of water needed is only 0,67 m^3/s; during the summer, the higher temperature will negatively affect the generation decreasing the efficiency; and during the winter, the higher temperature would affect the generation by increasing the efficiency allowing the power plant to generate more energy using less mineral coal.

Lastly, Lucena et al. (2012b) analyzed the impacts that global climate change could have on hydroelectric production in Brazil and concluded that the reliability of hydroelectric generation in Brazil could be compromised. In some regions, such as North and Northeast, hydropower production may be affected because the water availability in these regions is expected to decrease significantly. tTransmission lines all over the country can become more vulnerable to potential high winds, especially in the South, but the possible impacts cannot be predicted with currently available models; in some places, such as in the Parnaíba and Atlântico Leste basin, the average loss in electricity generated may exceed 80% (firm energy).

Many researches had been conducted in different countries, in order to assess the local / regional impacts of global climate change. All of them have similar conclusions, as Brazil is vulnerable to climate change because its high share of renewable sources, especially hydro, the wind potential in the shore area of north of Northeast region is expected to increase; the hydrogeneration in expected to dramatically reduce; and the impacts are also expected to reduce the biofuels production.

To reduce these negative impacts, it is necessary to reduce the GHG emission and implement adaptation strategies to decrease the vulnerability to those effects.

Information about GHG emission in Brazil is available in the Appendix A and Appendix B.

Vulnerability to climate change

The impacts resulting from changes in climate are directly connected to the vulnerability to which natural and human systems are exposed (Soito and Freitas 2011). One of the main effects of climate change is the increase frequency of extreme events. Figures 15 to 19 present the historic evolution of natural disasters in Brazil from 1991 to 2012.

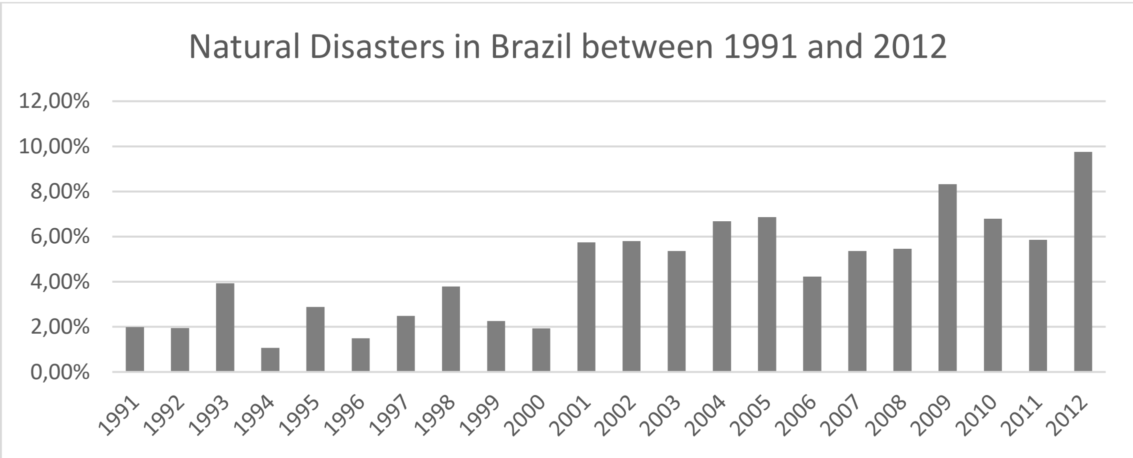


Figure 15: Total Natural Disasters in Brazil
Source: CEPED - Univeristy Center for Studies and Research on Disasters (2013)

Figure 15 shows the percentage of total natural disasters, occurred between 1991 and 2012. The concentration of disasters in the more recent years indicate an increasing tendency in the occurrence of these events.

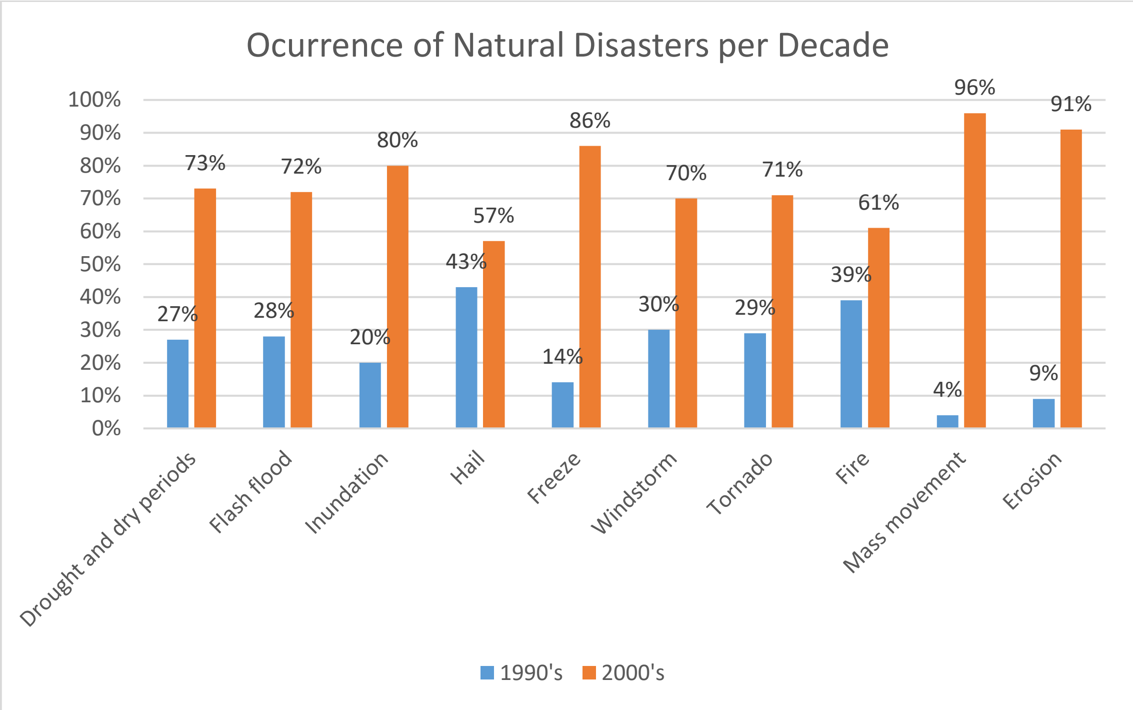


Figure 16: Comparative occurrence per decades
Source: CEPED (2013)

From Figure 16 it is possible to see the dramatic increase in the number of disasters, for all the types from the 1990 decade to 2000 decade.

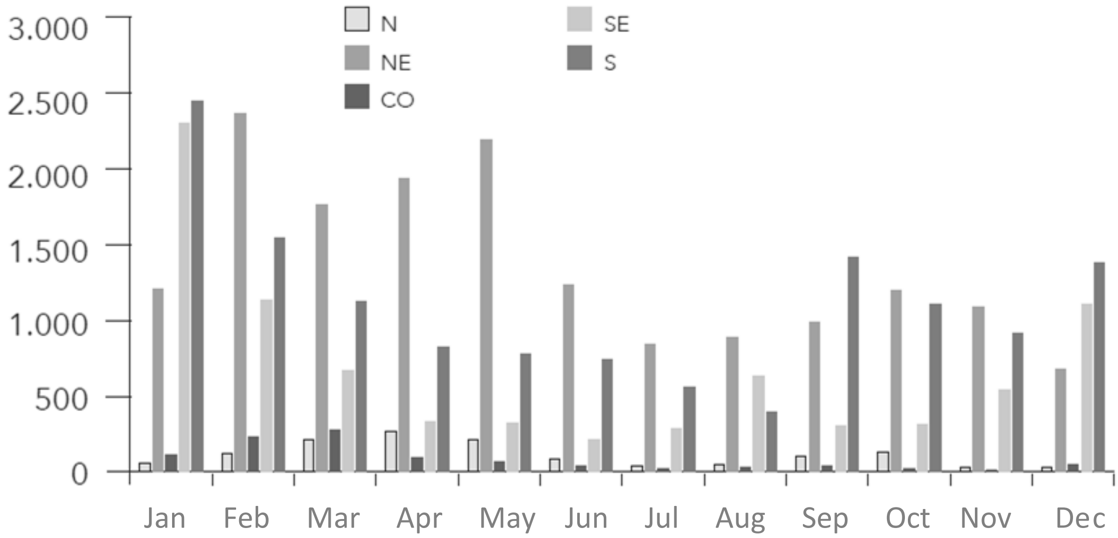


Figure 17: Mensal disasters occurrence per region
Source: CEPED (2013)

After analyzing each region, one can notice that the disasters have a seasonal behavior (see Figure 17) and it is slightly different for each region as they all have its unique climate and environmental characteristics.

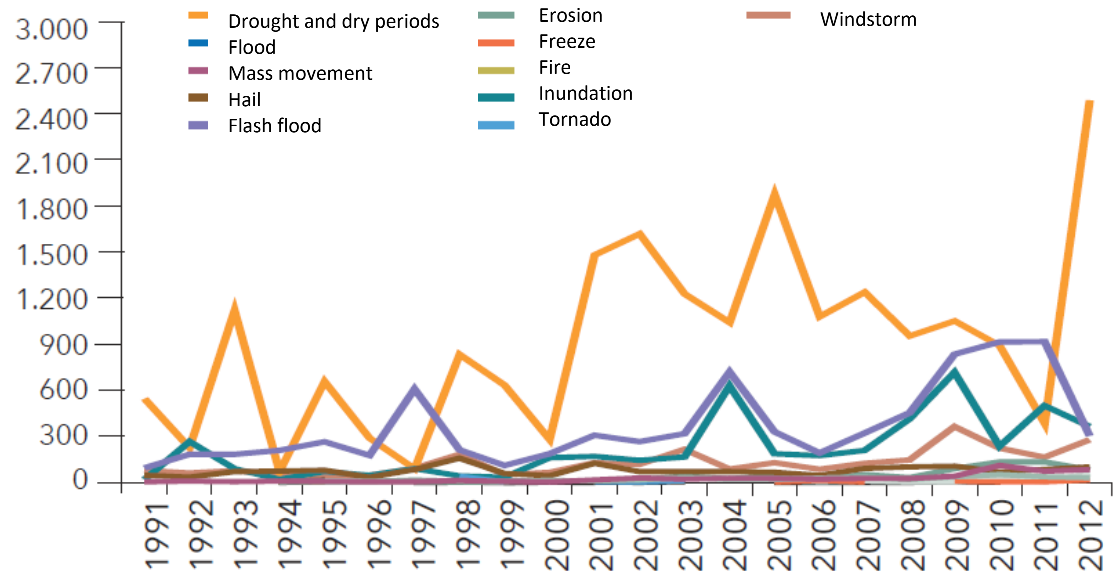


Figure 18: Comparative occurrence per year
Source: CEPED (2013)

The occurrence of drought and dry periods was very high during the second decade and had a dramatic increase during 2012.

It is also interesting to notice that flood and drought and dry periods presented a complementary behavior, one increases in the years when the other drops down.

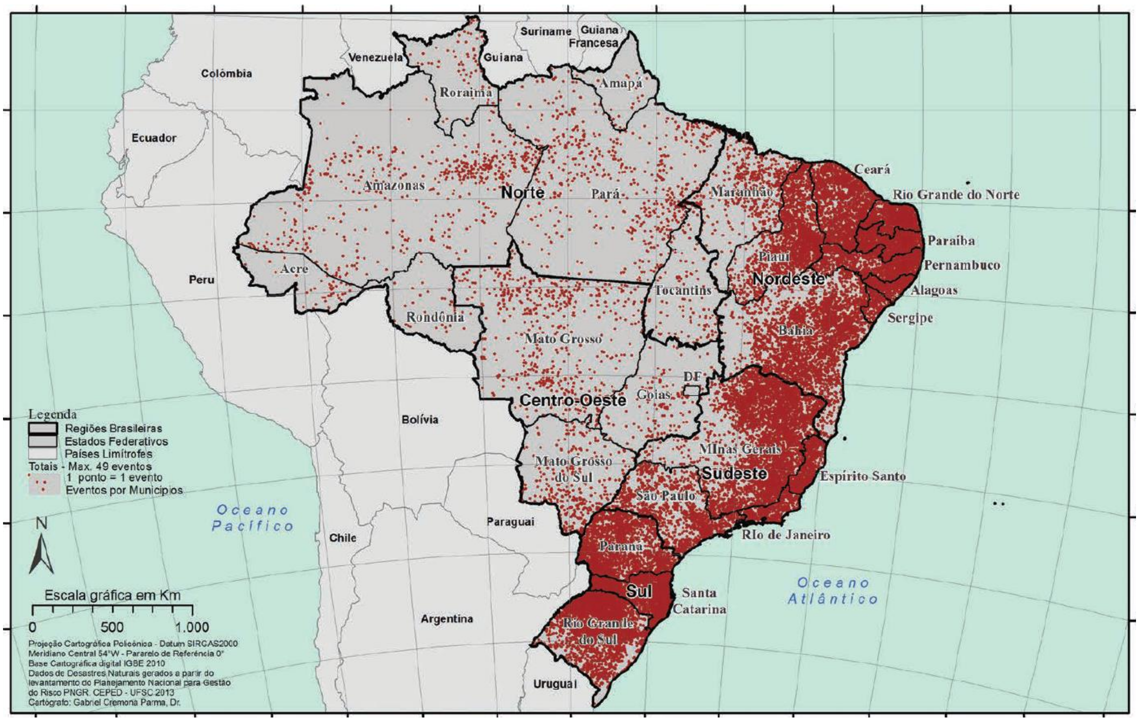


Figure 19: All events registered in Brazil between 1991 and 2012
Source: CEPED (2013)

Considering all the events, it is possible to conclude that the coastal area or, the most populous areas, are the most vulnerable areas to climate disaster in Brazil.

Other details on the occurrence of natural disasters in Brazil can be seen with more detail in CEPED (2013).

Major mitigation and adaptation efforts can reduce the magnitude of future impacts, but, given the specificities of each sector and region, it is necessary to analyze the expected impacts for the energy sector.

According to World Bank (2010) *apud* PBMC (2014), with regard to extreme events and its impact in Brazil, the country experienced the first hurricane ever observed in the South: Hurricane Catarina, occurred in March 2004. In the South and Southeast of Brazil, heavy rains have been more frequent in the last 50 years and agricultural productivity will be for sure affected, not only in these regions in Brazil but worldwide: However, that will happen especially in the tropics, threatening the food security of many countries.

Some researches were conducted with the purpose of identifying changes in the natural cycles, which can be related with the climate change. However, there are not many reviews of long-term variability and extreme weather and climate in the country (maybe because there is not enough history – climate changes are a recent phenomenon/research topic). Some studies have been done for specific regions such as South America, but one of the challenges that hamper the progress of this type of analysis has been the lack of weather information with good quality in long-term series.

The Amazon and northeastern Brazil constitute what might be called climatic change hot spots and represent the most vulnerable regions of Brazil to climate changes (Soito and Freitas 2011).

Furthermore, according to Lucena et.al (2012) the Brazilian electric system is very vulnerable to climate change because it is essentially renewable energy based and the concentration of the generation only in these sources exposes the system to extreme climate events, which can affect the ability of the country to attend the electricity demand.

However, even renewable energy being more vulnerable, due to its dependence to weather and climate, fossil energy supply technologies, though relatively less susceptible to variations in environmental conditions, are not totally free from eventual impacts from climate change (Schaeffer et al. 2012) as noticed in Arroyo (2012).

> In spite of the current high share of renewables in the Brazilian energy mix, the country faces a situation where, on the one hand, it needs to increase its energy production to foster socioeconomic development, job creation and poverty alleviation. On the other hand, the country faces the near exhaustion of its environmentally feasible hydropower potential and is expected to increase fossil energy use, with the recent oil discoveries in the pre-salt1 fields and the perspectives for increased coal-fired power generation (EPE, 2013; Nogueira et al., 2014; Saraiva et al., 2014 apud Lucena et al. 2015).

Additionally, Lucena et.al. (2012) also remember that, along the renewable sources vulnerability, because of an increase in environmental restriction to build new big reservoirs, the ability to compensate drought periods will decrease when the demand increases.

Moreover, according to Losekann (2015c), Brazil has a high risk of getting another electricity rationing, although, as presented in the Appendix B, the demand of 2015 showed itself below the expected one, even inferior to the previous year, which could be related to:

- Residential consumption: family income dropped down and the electricity is more expensive so, the consumption decreased;
- Industrial consumption: demand reduction increased the stocks and industries are not producing as much as before so, the electricity consumption decreased;
- Commercial consumption: increased, but analyzes considered Christmas time so, the increase can be temporary.

Considering the Brazilian power sector dependence on hydro and the impacts of climate change on rainfall, evapotranspiration and water availability in general, it is necessary to analyze the relationship water x energy.

In relation to Brazil, the country

> "holds the greatest reserves of surface water on the planet, about 19.4%, and one of the world's greatest potential water resources. However, it is not in a comfortable situation in terms of the availability of water resources and the location of the demands for its consumable and non-consumable. In fact, about 90% of the water is found in low-density drainage basins from the Amazon and Tocantins rivers, while about 90% of the population is supplied by the rest of the country's water resources" (Soito and Freitas 2011).

The most relevant characteristic of climate change, with regard to vulnerability and the adaptation of water resources, according to Soito and Freitas (2011) is related to noticeable alterations in the variability of hydrological systems and extreme events, and not simply to average tendencies in climate change. The authors say that “the occurrence of extreme events, such as droughts and floods, more often and more severely will increase conflict among water users in the various drainage basins of Brazil” (Soito and Freitas 2011).

In the power sector in Brazil, the hydropower may suffer with the water scarcity in the future. The Appendix C presents the level of the 22 main hydroelectric power plants in Brazil from 2000 until 2015. These figures show that the current levels of some reservoir are similar to the ones observed during the 2001 electric crisis. Considering that the hydropower is the main source of electric energy in Brazil it became a matter of concern.

Additionally, as noted by Lorenzo (2002), the severity of the 2001 situation (2001 energy crisis) stems from the fact that, simultaneously to the institutional crisis and the progressive increase in the risk in the electrical system, the reservoirs in the Southeast, mainly, come for declining for quite some time, reaching a level corresponding to 33% of its capacity, when the ideal would be about 90%.

In 2001, compared to a situation of low rainfall, the reservoirs were reduced to such a low level that was instituted a rationing policy. Lorenzo (2002) also argued that the consequences of the rationing announced in April of the same year were harmful to the population and especially for the production system and that the negative effects would be felt for several years. There is, however, a national recognition that the announced crisis was not more serious because of the prompt and positive response of society to request self-restraint in consumption and the relative economic decline of the country, which led to a lower growth of electricity demand by the productive sector (Lorenzo, 2002).

Besides, according to Losekann (2013), with the increasing demand and the environmental restrictions to build large reservoirs, the regularization capacity of reservoirs has dropped from 6 to 5 months in the last decade and will fall to 4 months until 2021.

Moreover, the hydrology is running below the long time average, which created a very worrying situation already called “ reservoir crisis” (Losekann 2015c).

Hydro source is present in the power generation mix of 159 countries but more than 50% of the total hydro generation in the planet come from five countries: China, Canada, Brazil, USA and Russia. However, the importance of hydroelectricity in the power mix of each of these countries is different: Brazil and Canada are heavily dependent on hydro having more than 50% of hydro generation in its total generation, each; US has less than 10%; Russia and China have between 10 and 20% (Soito and Freitas 2011).

Hydro electricity is very important in the Brazilian mix but, with climate change, it is also a source of concern. Lucena (2010) pointed out the reduction in the firm energy[10] associated with each basin, which could achieve 80% in some of them (see Table 12).

Table 12: SUISHI-O model results by Lucena

Basin	**Historic**		**Variation in Relation to the Reference Scenario**			
	Average MW*		A2		B2	
	Firm Energy	Average Energy	Firm Energy	Average Energy	Firm Energy	Average Energy
Amazonas	9425	10628	-36%	-11%	-29%	-7%
Tocantins Araguaia	7531	10001	-46%	-27%	-41%	-21%
São Francisco	5026	5996	-69%	-45%	-77%	-52%
Parnaíba	236	293	-83%	-83%	-88%	-82%
Atlântico Leste	496	565	-82%	-80%	-82%	-80%
Atlântico Sudeste	1937	2268	-32%	1%	-37%	-10%
Atlântico Sul	1739	2037	-26%	8%	-18%	11%
Uruguai	1715	1996	-30%	4%	-20%	9%
Paraguai	375	426	-38%	4%	-35%	-3%
Paraná	22903	29038	-8%	43%	-7%	37%
Total	**51382**	**63247**	**-31,5%**	**2,7%**	**-29,3%**	**1,1%**

Note: Based on the system configuration designed for 2016 (EPE, 2007b).

*: MWm indicates an amount of energy generated according to the average capacity factor

Source: Lucena (2010)

Although the average total energy kept itself almost constant in both, A2 and B2, scenarios, the firm energy decreased almost 30%, which means that even though the

[10] The concept of firm energy refers to the actual energy guaranteed to be available, i.e. non-interruptible energy and power guaranteed by the supplier to be available at all times, except for uncontrollable circumstances

average system, as a whole, will not suffer much with the climate change, in some periods the system will lose a huge amount of its capacity to generate energy Lucena (2010).

Therefore, when considering the expansion plan for the electric system, Lucena (2010) suggested that another source would be needed for complementary purposes and, as it would be used for small periods, it should be based in low-cost capital plants, and should have good operational / contractual flexibility.

Another variable that was used is the capacity factor and it was calculated by Lucena (2010) and is presented in Table 13.

Table 13: Changes in the capacity factor

		Historic	**A2**		**B2**	
Subsystem		Capacity Factor	Variation vs Reference	Capacity Factor	Variation vs Reference	Capacity Factor
S/SE/CO	<30 MW	**58.0%**	-30.7%	**40.2%**	-31.7%	**39.7%**
	[30; 300] MW	**48.5%**	-34.9%	**31.6%**	-33.9%	**32.1%**
	>300 MW	**44.6%**	-13.2%	**38.7%**	-11.4%	**39.5%**
N/NE	<30 MW	**58.0%**	-25.2%	**43.4%**	-15.8%	**48.8%**
	[30; 300] MW	**42.4%**	-49.4%	**21.5%**	-45.1%	**23.3%**
	>300 MW	**49.6%**	-48.5%	**25.5%**	-45.9%	**26.8%**

Source: Lucena (2010)

Table 13 presents a significant decrease in the firm capacity factor of the large and medium-sized plants in the north and northeast of almost 50%. According with Lorenzo (2010), this is a consequence of falling water alterations in climatic scenarios A2 and B2. In practice, this means that the amount of energy that can be guaranteed though hydroelectric generation is smaller.

Finally, in order to reduce the vulnerability of the power sector, without backtrack in the renewable participation, some mitigation strategies were proposed in the literature and those will be discussed in the next topic.

Mitigation and Adaptation

In Brazil, distributed generation, which could be a good mitigation and adaptation strategy, according to Losekann (2015c), is not presenting itself very successfully, especially because of the costs, which are not interesting to the market.

However, according to Ferraz (2015b), the resolution 482 made possible to introduce microgeneration in the grid and the agreement with National Council of Finance Policy states to exclude the microgeneration of the ICMS (tax on the movement of goods and services), which is the one that has more weight in the electricity tariff.

Ferraz (2015a) also says that, the diffusion of solar energy in Brazil has been very slow, and this is explained by several reasons. The main one is that solar has more competitive advantages when compared to the other sources in the distributed microgeneration, but this is a great innovation for the Brazilian electrical sector, historically organized towards great projects to be dispatched centrally. So, adopting distributed microgeneration also implies a great change of organization and regulation structure.

Furthermore, according to Ferraz (2015c), the new renewable sources will not just add more energy into the grid; they cannot be treated as any other source because of their flashing nature, which makes necessary to change all the system.

As the renewable sources generate energy when they have weather/climate conditions to do it and not when the system's controller decide it, a more robust system and smarter transmission and distribution systems are needed.

Ferraz (2015c) explains how wind and solar energy are going to operate in a very different way in Brazil as the solar energy will get in as microgeneration, which will affect the distribution. For the last ones, the solar microgeneration is not interesting because the companies will become responsible for new functions (they will be required to know how much each residence produced and treat the account differently) and will not be paid to do that. Besides, the distribution companies will lose profit, after all, as consumers will buy less energy to produce their own.

Besides solar energy, the expansion of wind also represents a good strategy, especially because Brazilian natural characteristics offer interesting complementarities between wind and water resources in some regions of the country (more wind when has less precipitation and vice-versa), which can help optimize the SIN operation.

Another observed strategy in Brazil to assure the supply of future demand is seek to “establish agreements with bordering countries looking for regional energy integration” and “besides the Binational Itaipu Hydroelectric, involving Brazil and Paraguay, the current setup includes interconnections between Brazil and Argentina, Uruguay, Venezuela”. Moreover, hydropower inventory studies are being performed in Guyana, whose potential is about 7.5 GW” and it is possible “to negotiate a construction of one or two power plants in this country to import part of the electricity produced” (Soito and Freitas 2011).

Finally, as pointed by Lucena et al. (2010), “long-term energy planning in Brazil has not yet analyzed or assessed the possible impacts of global climate change scenarios on the vulnerability of the Brazilian energy system in general, and in its power system in particular”. Although, the early pre-reports from the PNE 2050 mentioned climate change, the final plan is not ready yet and the way in which climate change will be considered in the next energy expansion plan is still unknown.

As this research aim to evaluate the possible contribution of smart grid to reduce the vulnerability of the Brazilian power, sector in the future, the next topic addresses the status of smart grid research and implementation in the country.

Smart Grids in Brazil

In Brazil, the electric power system is based on big power plants, mostly hydro. As the generation is far from the big consumer centers, the utilization of a high voltage transmission system for big distances is necessary. Then, the energy is conveyed to the distribution system towards the consumer centers, following the classic structure from high to medium and finally to low voltage levels.

Although the generation and transmission systems have a fairly advanced monitoring and controlling levels, the majority of the distribution system does not have monitoring, control or associated communications networks functions (Pelegrini and Vale 2014).

In the world, the stakeholders in the electricity sector are facing big changes and fast evolutions in the market and environment. In Brazil, where the environment is highly regulated, the companies must live with regulatory uncertainties and prepare strategies to mitigate risks including the implementation of new technologies (Pelegrini and Vale 2014), as smart grids.

Knowing that each country or region has its own reasons and motivations to implement smart grids. The Brazilian's motivations for smart grid reflect the stakeholders' reality which were summarized by Pelegrini and Vale (2014):

- Possibility to reduce the operational costs of the system due to an increase in the operational efficiency because of the automation of internal processes and development of system management provided by a greater monitoring and control of all agents involved in the operation;
- Expectation of better management of company assets, from the better maintenance policies and replacement of these assets based on the use of tools that enable planning of maintenance based on the actual condition of the equipment;
- Consequence of the society's requirements for more quality in the energy supply;
- Opportunity to protect the income and fight the losses, especially the non-technical ones, which are very high in the country.

According with the Brazilian Industrial Development Agency and Institute of the Association of Proprietary of Business Infrastructure and Private Telecommunications Systems (*apud* Pelegrini & Vale, 2014) there are more than 200 projects about smart grids, which involves 450 institutions, 300 suppliers, 126 research centers, 60 power sector utilities, ministries, regulatory agencies and universities.

Furthermore, in Brazil, the smart grid pilot projects can be divided in ten subthemes according to Pelegrini and Vale (2014):

- Smart meter;
- Distribution automation;
- Storage systems;
- Electric vehicles;
- Telecommunications;
- Information technology;
- Smart buildings and houses;

- New services; and
- Others (related to costumers, IP, cybernetic security, asset management, among others).

In Brazil, some pilot projects are under development to study the market in relations to some smart grid’s technologies and Table 14 presents the main pilot projects under development in Brazil.

Table 14: Main smart grid pilot projects in Brazil

Name	Local	Utility	Goal	Intention
Smart city	Búzios/RJ	Ampla Utility	Validation and replicability	The utility aims to build the first smart city of the Latin America
Smart grid program	Barueri e Vargem Grande Paulista/SP	AES Eletropaulo utility	Validation and replicability	The program, aims to evaluate a smart grid in a representative scenario of the utility area aiming to replicate the model to other serviceable areas.
InovCity	Aparecida/SP	EDP Bandeirante	Creation of a sustainable smart grid model with national visibility	The utility's aim is the operational cost reduction and model replication to other Brazilian cities; however, the replicability depends on consumer engagement and Brazilian regulation about smart grids
Cities of the Future	Sete Lagoas/MG	Cemig utility	Validation and replicability	The region was selected for having a favorable electric system and communication, diversified market and for representing a sample of the utility market.
Parintins project	Parintins/AM	Eletrobras utility	Creation of a sustainable smart grid model with national visibility	The region was selected for having an off-grid power system, which favors tests on distribution grid under stress situations. The utility aims to observe the new technologies from generation to consumption of electricity, besides the consumption behavior, and to replicate the pilot project to other serviceable areas
Fernando de Noronha project	Fernando de Noronha/PE	Companhia Energética de Pernambuco (CELPE)	Creation of a sustainable smart grid model with national visibility	It has been selected a region which has high environmental restrictions, an off-grid power system, and harsh conditions as high temperature and salinity. The utility aims to build a smart grid on a controlled and high environmental restrictions area to evaluate the real contributions and problems elapsed, including sustainability, security, energy quality and energy efficiency aspects.
Paraná smart grid	Curitiba/PR	Companhia Paraense de Energia (COPEL)	Validation and replicability	The region was selected for having a high-density population and for representing a sample of the utility market.

Note 1: More detailed information in the Appendix D.

Source: Redes Inteligented Brasil, 2015 and Di Santo et al. 2015

According to (ANEEL 2010), some technological changes (technological migration related with smart meters) are already happening. However, ANEEL emphasizes that these new meters are not able to provide additional features that would allow a full development of smart grid and can became obsolete after few years. That is happening because of the lack of incentives and coordination of this migration, inducing distributors to adopt their individual solutions to their particular problems.

Smart grid is expected to increase electricity reliability by, among other ways, increasing the flexibility of the system. System flexibility and smart grid approaches are expected to contribute for the integration of intermittent sources. For instance, in Ireland, it was estimated to facilitate real-time penetrations of wind up to 75% by 2020 (EirGrid, 2010 apud IEA 2011). The problem with wind intermittency in Brazil was already pointed as one of the main reasons why wind is not being properly introduced in the country's grid.

Besides the intermittent sources integration, other projections were already made in Brazil and some other countries. The projections of the Working Group on Smart Grids (2010) are summarized in Table 15.

Table 15: Projections for the Smart Grids Benefits

Assumption	Values	Author	Comments
Reduction of peak [1]	Reduction of 5-10%	British regulator OFGEM, 2006	From the potential of consumers to save energy by applying hourly tax. There are inaccuracies in this estimate and the evidence for this finding is not strong.
	Average reduction of 3.5% in a year	Northern Ireland – study about the impact over energy efficiency, OFGEM, 2006	3 different hourly taxes were used during 4 periods. The night peak could be reduced until 10% according with the price. A high level of consumer satisfaction was reported in the trial, with monetary savings calculated from 1.5% for the average, up to 15% for some consumers.
	Reduction of 15%	U.S. Department of Energy	Use of a sophisticated system that responds to simple instructions set by the consumer. Consumers reduced about 10% in their bills. Enabled the grid, which was previously saturated, serves for a further period of 3 to 5 years of peak load growth.
	Average reduction of 13% during peak	California, Brattle Group, 2007	Used different tax during 3 years by 3 utilities. The reduction of 13% happened during the 6 months of summer time (from May to September). Consumers who had an intelligent thermostat reduced their load by 27% and those who had the gateway system reduced their load of 43%. Based on the uncertainties of behavior the study used Mont Carlo to have a solid result and by doing that generated an estimated maximum demand reduction by 5%.
		Brazil, Copel, 1998	229 consumers. Used an increase in the tax during peak and a decrease out of peak. The pilot project showed that 70% of consumers made a beneficial behavior change because of the tax change.

	Reduction of 500W/consumer	Guarulhos – SP, Brazil, Bandeirante, 1998	2354 (>250 kWh/month) consumers used a differentiated tax and a Two Way Automatic Communication System – TWACS.
Reduction of non-technical losses [2]	Reduction of 4,73% in 4 years	Ampla, Brazil	A distributor utility implemented smart meters in regions with very high losses levels. Besides the use of smart meters Ampla also concentrated the measurement, armored electrical networks and raised the low voltage cables.
Reduction of losses [3]	Reduction of 9,6% in low voltage		Nowadays the technical losses represents 28 TWh/year, or 7,3% of all electric energy injected into the grid. By assuming a reduction of 5% during peak and 1% in total consumption and using the regulated methodology available in Módulo 7 do PRODIST was possible to calculate the reduction.
	8%	Brattle Group, 2007	The study "The Power of Five Percent - How Dynamic Pricing Can Save $35 Billion in Electricity Costs" shows that a reduction of 5% in the demand would reduce the losses by 8%
Reduction in the total consumption	1%	Brazil, Working Group on Smart Grids	Change in consumers behavior by the use of seasonal rates

1 The Working Group on Smart Grids adopted a peak reduction of 5% and a total consumption reduction in low voltage of 1% in order to have a conservative approach.

2 The Working Group on Smart Grids to estimate how much the non-technical losses would be reduced was adopted a procedure that examined non-technical losses in each of the distributors in the country, considering: the current level of losses; the combat actions already taken; and the social reality of each concession area. See Table 17 for more information on the assumptions for non-technical losses.

3 The Working Group on Smart Grids considered that a demand during peak reduction of 5% and a total demand reduction of 1% is the same as a 9% reduction of technical losses in low voltage; 1,2% reduction in medium voltage, which means a total reduction from 7,27% to 7,20%.

Source: Working Group on Smart Grids (2010)

Tables 14 and 15 presented the estimated benefits of smart grids implementation in some countries, including Brazil. However, it is not possible yet to see if these benefits are enough to adapt the sector to climate changes or to reduce the GHG emission per MW produced, as it has been increasing during the last years. Besides, Borba et al. (2012) concluded that the mitigation potential identified in the country was not large enough, in absolute terms, to reduce energy-related GHG emissions below the current level in Brazil by 2030.

In this research it was decided to use conservative values for smart grid's benefits, following the assumptions adopted by the Working Group on Smart Grids (2010).

In relation to the non-technical losses, Table 16 presents the relation between system losses and the projected improvements in non-technical losses, after implementing smart grids in Brazil.

Table 16: Projections for non-technical losses reduction

Currently Losses	Losses after Smart Grid	Number of Distributors
< 3,5%	Stay the same	33
[3,5%; 5%]	3,5%	03
[5%; 6%]	4,5%	04
[6%; 8%]	5,5%	08
[8%; 10%]	7%	03
[10%; 15%]	9%	02
> 15%	10%	07

Source: Working Group on Smart Grids (2010)

The numbers presented in Table 17 values result from a study involving a group of 48 distributions companies (out of 63[11]). Table 17 presents the final results of this analysis.

Table 17: Projections for non-technical losses reduction considered 100% penetration of smart gridws in this 48 distributions companies market

Currently Losses	Losses after Smart Grid	Number of Distributors	Currently Losses (Thousands of R$)[1,2]	Losses after Smart Grid (Thousands of R$)[1,2]	Currently Losses (TWh) [1]	Losses after Smart Grid (TWh) [1]
< 3,5%	Stay the same	30	1.118.050	1.118.050	4,916	4,916
[3,5%; 5%]	3,5%	5	172.501	154.264	1,653	1,448
[5%; 6%]	4,5%	2	89.847	71.586	0,670	0,565
[6%; 8%]	5,5%	2	59.429	44.579	1,407	1,061
[8%; 10%]	7%	0	-	-	-	-
[10%; 15%]	9%	3	93.276	69.990	2,560	1,951
> 15%	10%	6	194.546	113.061	7,843	4,801
Total		48	1.727.649	1.571.531	19,049	14,741
Difference			-9,04%		-22,62%	
Total Reduction			156.118		4,308	

Note 1: Base year 2015
Note 2: Sum of the individual losses of each company in this group

[11] The limitation is due to lack of data from other companies.

Lastly, even with the expected good results, the implementation of smart grids presents some challenges (ANEEL 2010):

- Integration of distributed generation and renewable sources in the grid;
- Development and patronization of smart grid technologies;
- Utilization of demand side management;
- Development of market technologies;
- Demand response technologies;
- Socio-economic and tax analysis;
- Laboratory tests and certification for all the different new technologies;
- Initiatives of demonstration projects;
- Professional capacitation, training and qualification;
- Definition of funding sources;
- Telecommunication structure;
- Society awareness.

Smart grid scenarios' synthesis

The scenarios description and characteristics were presented during the explanation, which took place along the Chapters III and IV. However, to facilitate the interpretation, a digest version is presented below.

Table 18 presents the combination of settings considered to define each scenario, the years analyzed, and the code used for each of them.

Table 18: Scenarios used in the case study

Economic, social and technological	Smart Grids Implementation	Year	Acronyms
Current Account		2015	CA
Reference			REF
	Slow	2030	SG_S
	Moderate	2030	SG_M
	Fast	2030	SG_F
Reference A2			REF_A2
	Slow	2030	A2_SG_S

	Moderate	2030	A2_SG_M
	Fast	2030	A2_SG_F
Reference B2			REF_B2
	Slow	2030	B2_SG_S
	Moderate	2030	B2_SG_M
	Fast	2030	B2_SG_F

The variables evolution in each scenario are described below:

- Population:
    - CA – 205,27 million inhabitants according to the IBGE (Brazilian Institute of Geography and Statistics) estimations;
    - Other scenarios – 208 million inhabitants based on Institute of Economic and Applied Research projections
- GDP:
    - CA – 1812,28 billion Reais, local current unit according to Brazilian central bank;
    - Other scenarios – 3,2% annual growth according to PNE 2030 B2 scenario projections;
- Total Demand:
    - CA: 522,72 TWh according to BEN (EPE/MME 2016)
    - REF: 971 TWh based on the projection presented in the PND 2050 (EPE 2016)
    - SG scenarios: was considered a reduction of 1% in the total consumption based on a conservative projection made by the working group on smart grids (2010);
    - A2 scenarios: was considered an increase in residential demand (increase of 3,21% per year) and commercial demand (total increase of 19% over the projected demand for 2030) due to an increase in use of air conditioner – considered the increase of numbers of hot days, so more days in the year when the air conditioner will be used, and hotter days, so, more times in the same day, the air conditioner will be working; the other sectors were not considered in this analysis and the demand was considered the same as the REF scenario (Lucena 2010; EPE 2007);

    - B2 scenarios: was considered an increase in residential demand (increase of 2,79% per year) and commercial demand (increase of 4,6% per year). Even with an increase in use of air conditioner the B2 scenarios family consider a sustainable growth, which implies the implementation of more sustainable and efficient equipment, lamps, showers, etc; the other sectors were not considered in this analysis and the demand was considered the same as the REF scenario (Lucena 2010; EPE 2007);
- Losses:
    - CA: 15,11% according to EPE BEN 2016
    - REF: 14,29% based on the projection presented in the PND 2030;
    - SG scenarios: was considered a reduction in the total losses based on Table 17, in this chapter, based in the projected reductions made by Working Group on Smart Grids (2010);
- Imports:
    - CA: 34,273 TWh according to EPE BEN 2016
    - Other scenarios: sufficient energy to attend the demand considering the expected technical and non-technical losses;

More information about the variables evolution and projection see Appendix F.

Now that all the scenarios information was given, the next topic presents the results of this research.

Impacts of Smart Grids as an adaptation and mitigation strategy

After evaluating smart grid's technologies as a GHG reduction option, the baseline scenario was developed estimating GHG emissions, assuming that current development trends continue, and no actions are undertaken to explicitly reduce these emissions. The next phase considers the alternative GHG mitigation scenarios, as explained before.

Figures 20 to 29 presents a synthesis of the core features of the Brazilian energy sector projected for 2030 as well as the main results obtained in this research.

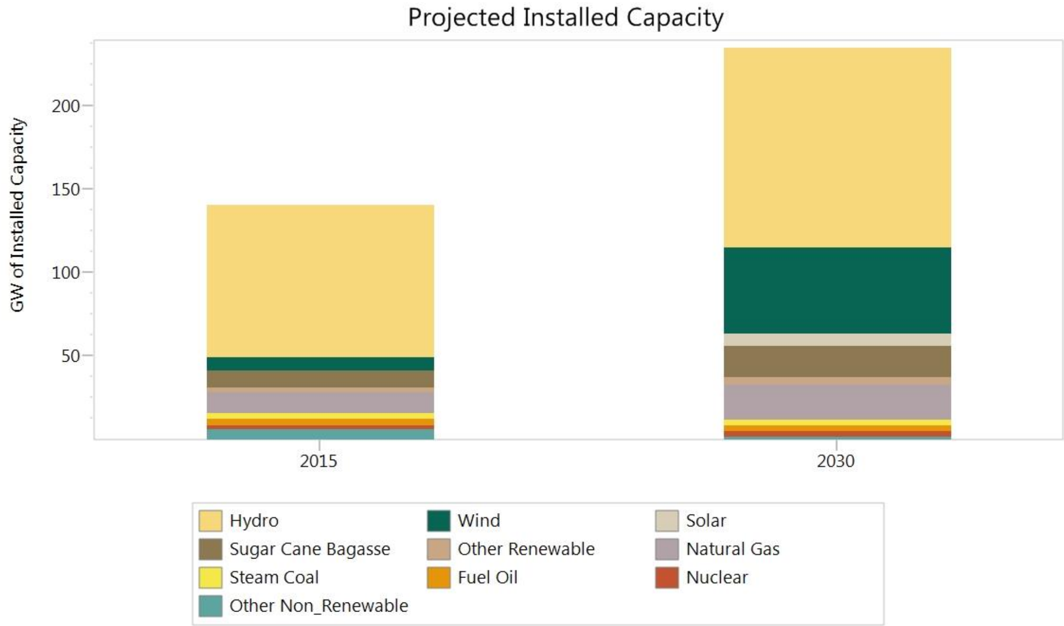


Figure 20: Installed Capacity by Source – present and 2030

The increase in the installed capacity took into consideration the projections presented by PNE 2030 and the annual PDE's projections and the real values, i.e., which was really build out of what was planned.

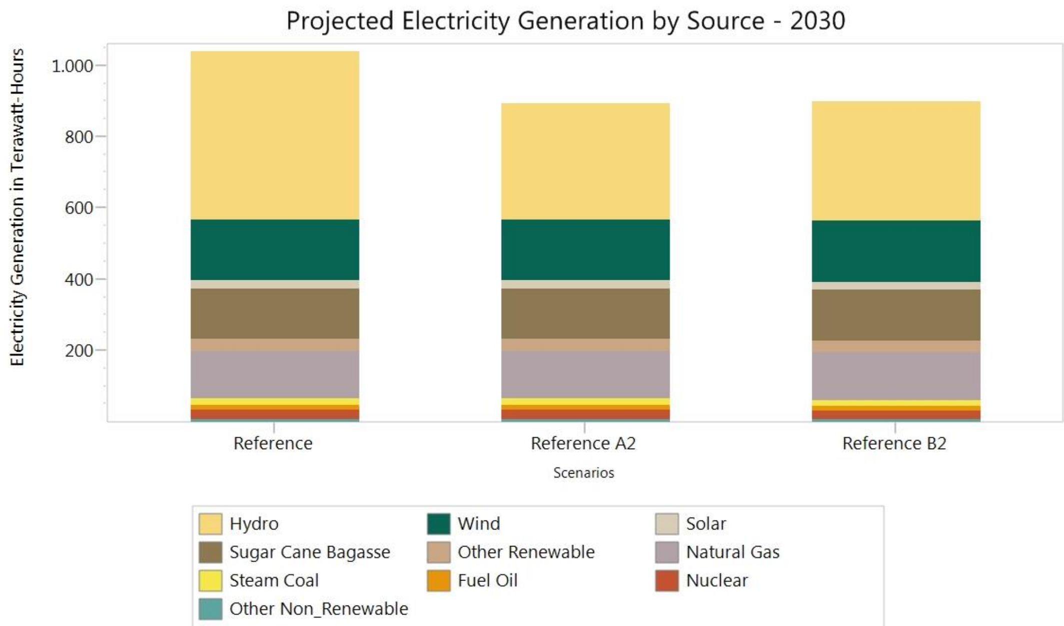


Figure 21: Generation by source 2030

Figure 21 presents the projected decrease in Hydro generation from the reference scenario to the A2 and B2 scenarios due to reduction of capacity factor and firm energy. The

Scenario A2 has a small difference in hydro generation when compared to the scenario B2 (A2 324,8 TWh and B2 334,3 TWh).

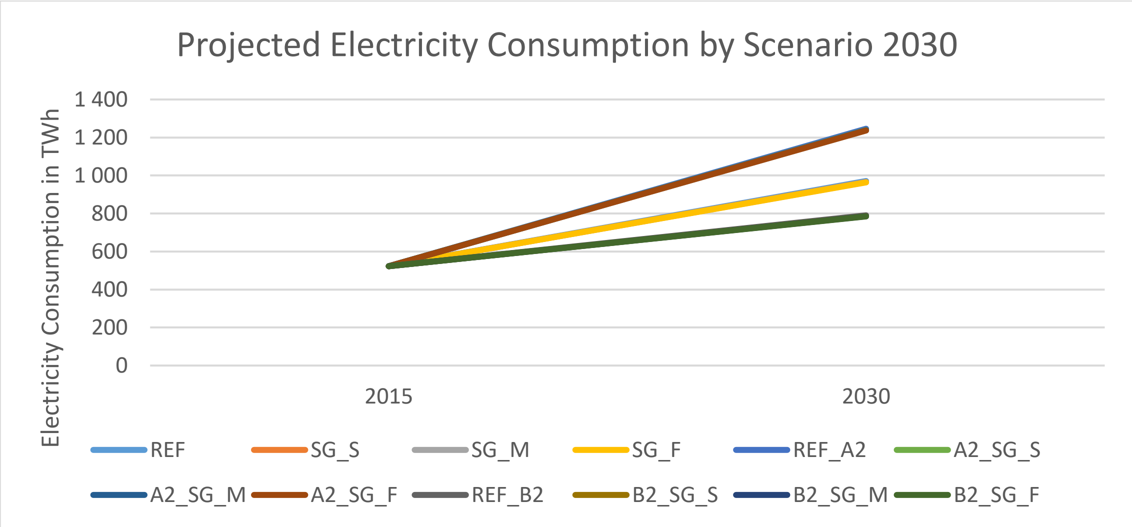


Figure 22: Total Demand in 2015 and 2030

In Figure 22, the demand can be separated into 3 groups: the middle one is the Reference scenario; the A2 group (lines in the top) projected a demand much higher as it anticipates a large increase of air conditioner use in residential and commercial sectors; and the B2 group (bottom lines) presents the smaller demand as it considers the use of more efficient electrical equipment even considering the increase in air conditioner use. According to these results, the transition to smart grids does has a negligible impact on the total demand.

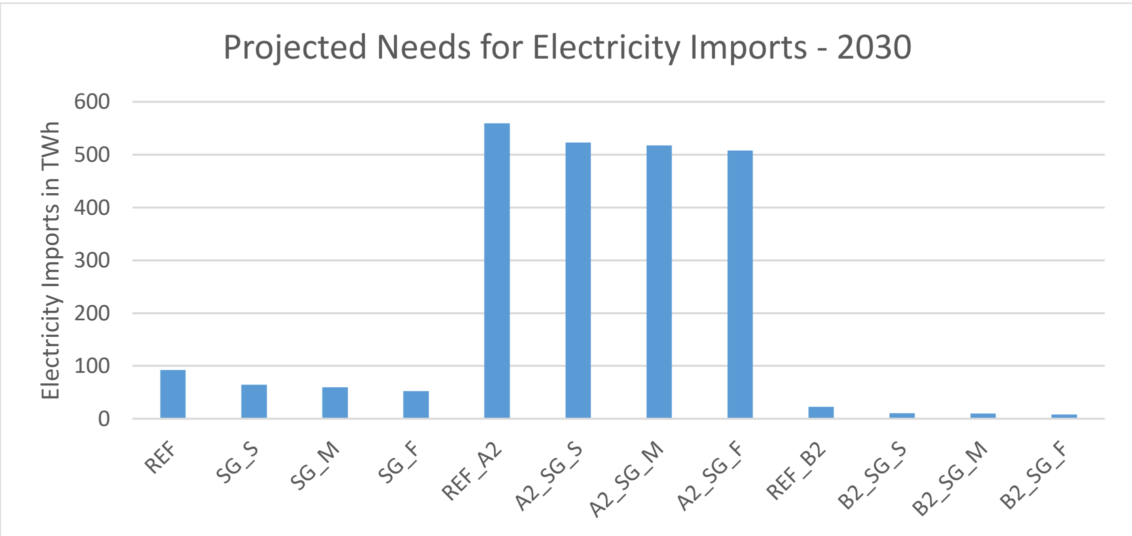


Figure 23: Projection of need of electricity imports in 2030 per scenario

Even considering the decrease in hydro generation the need to import electricity is smaller in the B2 scenarios than it is in the reference scenario due to the demand reduction. The use of smart grids decreases even more the need of importing energy.

However, it is important to remember that the need to import electricity does not corresponds to the real importation as, for example, it would be better to import electricity from the Paraguayan part of Itaipú Binational than produce it from thermal generation as it is less expensive and clean[12].

In what concerns the emissions, Figure 24 shows the direct and indirect (without counting twice the same emission) GHG emissions represented in CO_2 equivalent 100-years GWP (global warming potential).

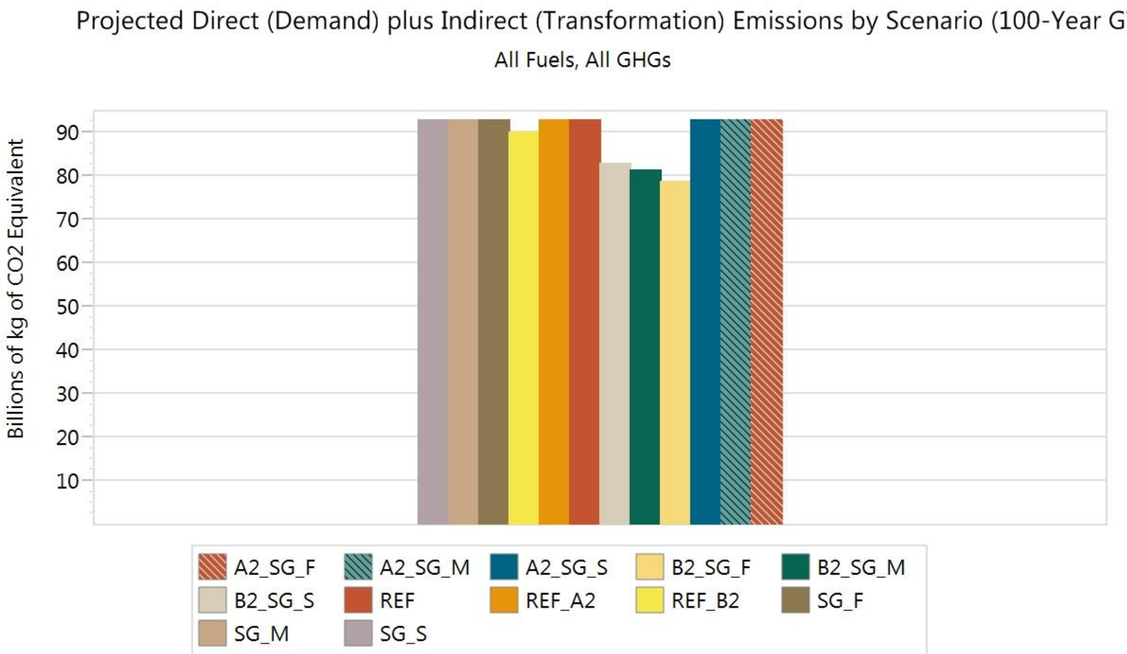


Figure 24: Projected CO_2 equivalent emission by scenario

As shown by Figure 24, the emissions are very similar in all the scenarios with the exception of the B2 group. As the A2 and the REF groups work with the exhaustion of the system as the capacity is not enough to attend the increasing demand.

[12] Regarding electricity, almost all imports correspond to the purchase of the part of Itaipú Binacional's energy from Paraguay, which represented 5.8% of the electricity supply in the SIN in 2014 (EPE/MME 2015a).

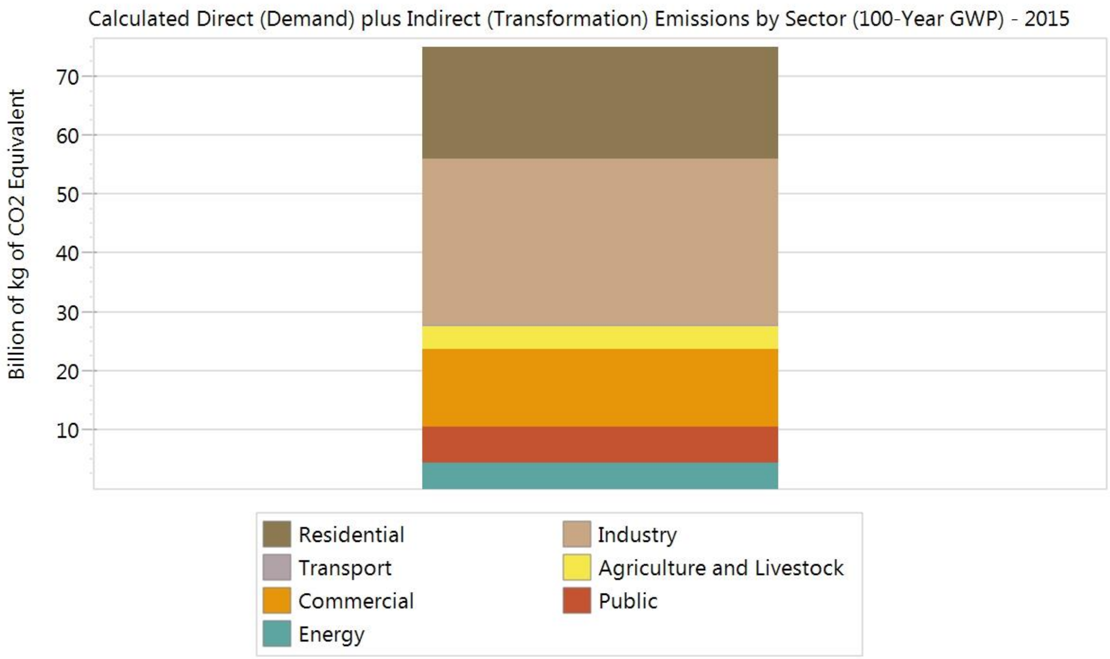


Figure 25: Calculated emissions by sector - 2015

Figure 25 presents the estimated emissions for 2015, in order to compare it to the ones presented in Figure 26.

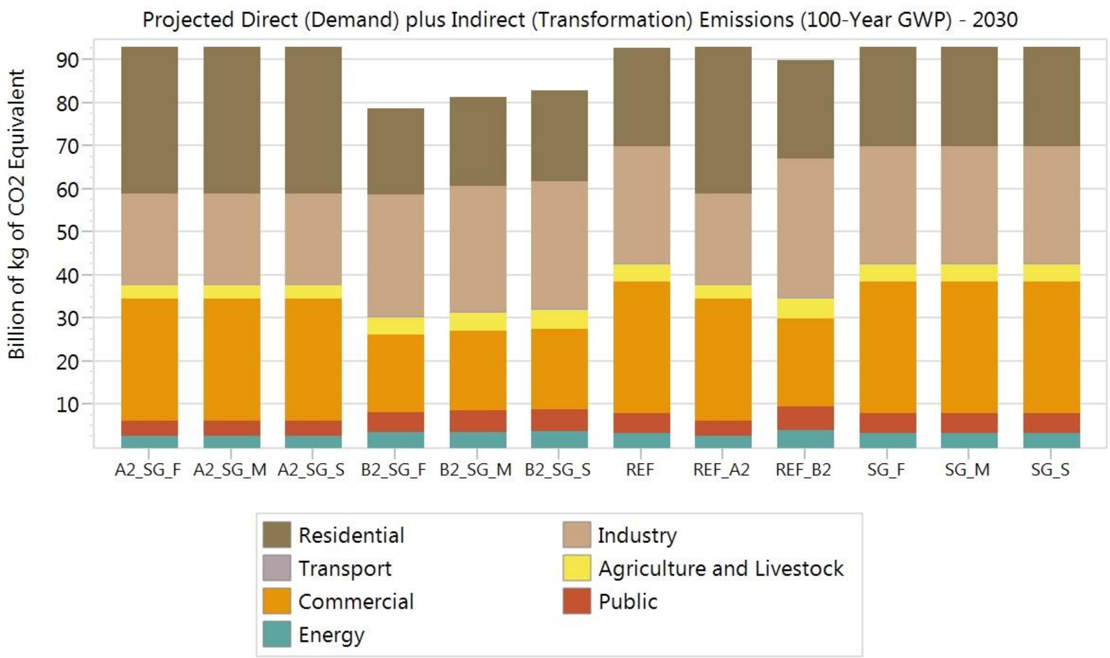


Figure 26: Projected emissions by sector – 2030

Figure 26 shows the emission by sector. There is a slightly difference when comparing the same sector between the scenarios. This difference is due to the projected final energy mix for each scenario.

The next figures, Figure 27 to 45, present the historical evolution followed by the projected one: generation by scenario, demand by sector and emission obtained as a result from the LEAP analysis.

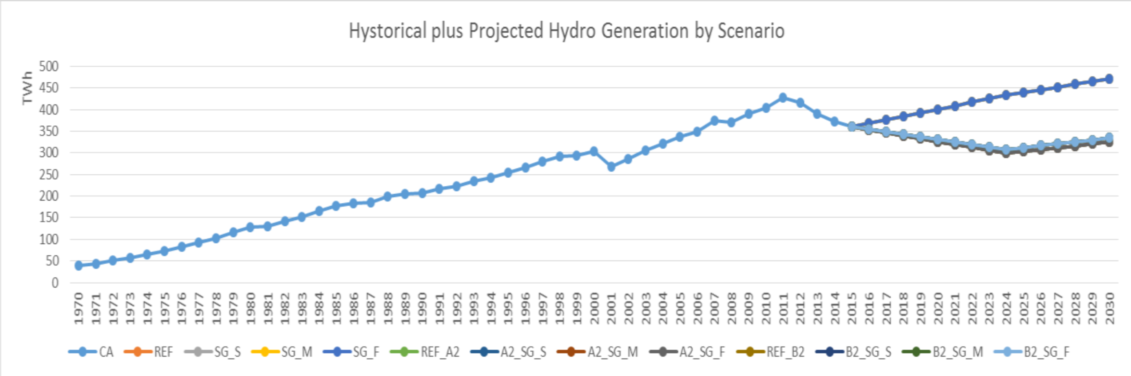


Figure 27: Historical plus projected hydro generation by scenario

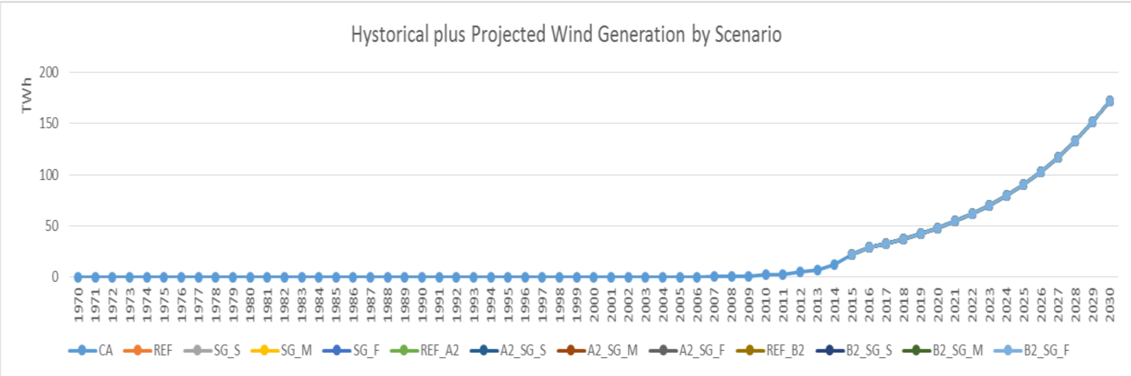


Figure 28: Historical plus projected wind generation by scenario

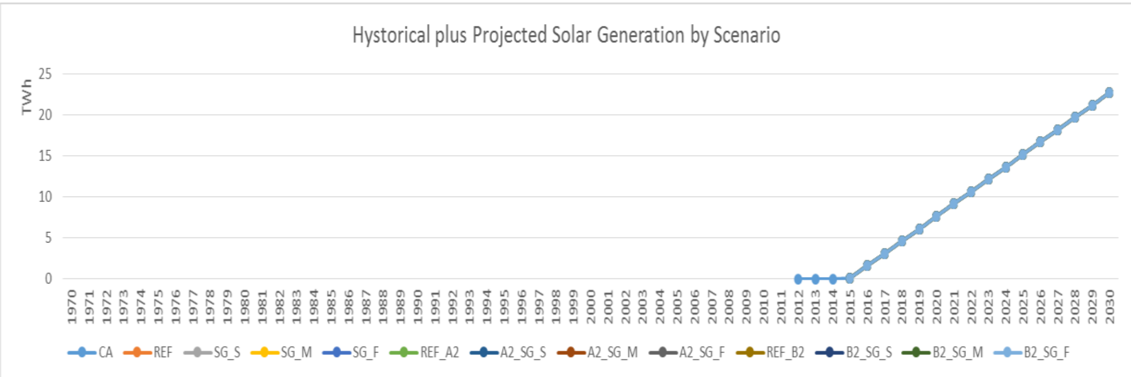


Figure 29: Historical plus projected solar generation by scenario

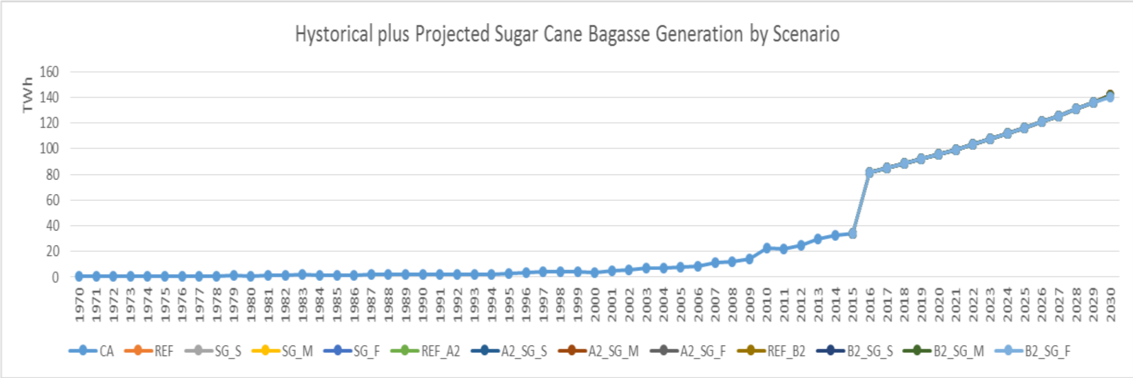


Figure 30: Historical plus projected sugar cane bagasse generation by scenario

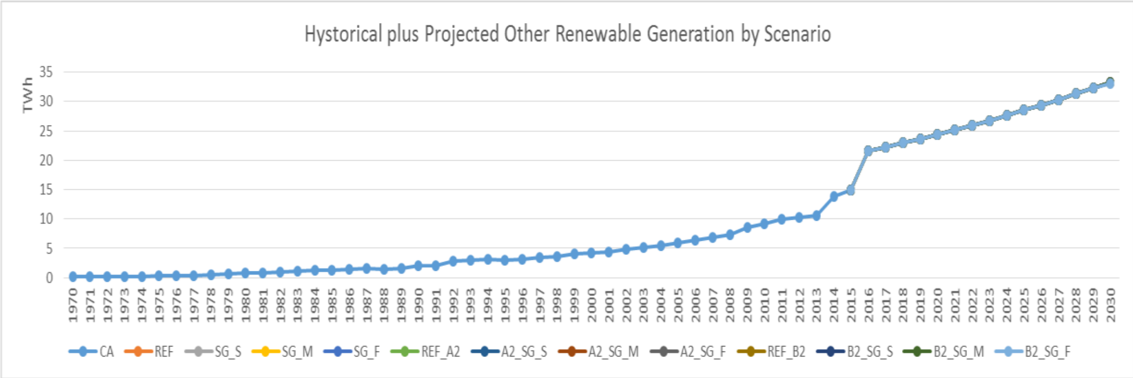


Figure 31: Historical plus projected other renewable generation by scenario

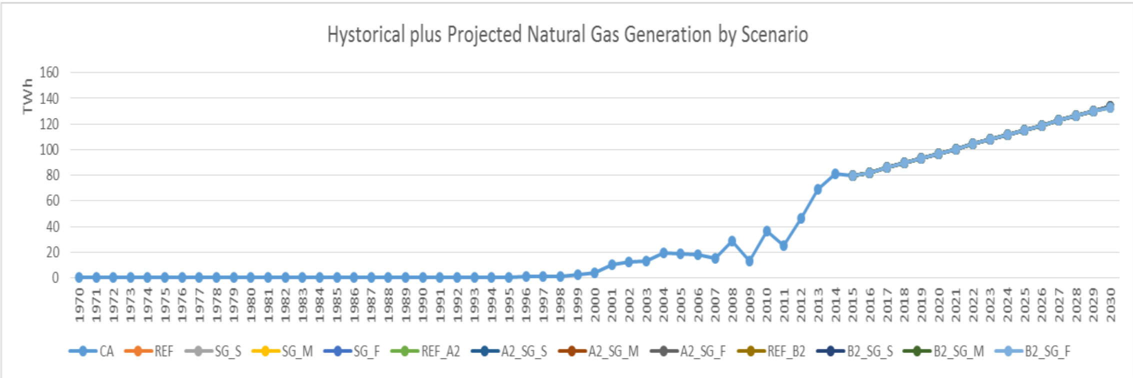


Figure 32: Historical plus projected natural gas generation by scenario

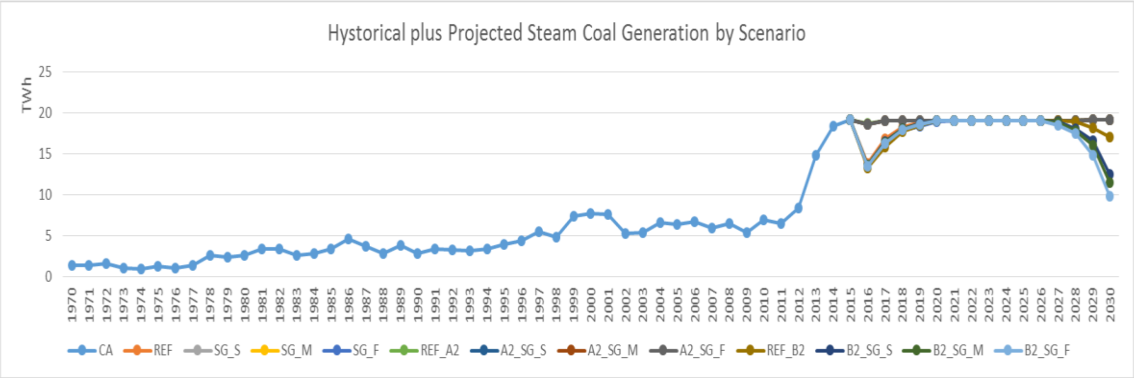


Figure 33: Historical plus projected steam coal generation by scenario

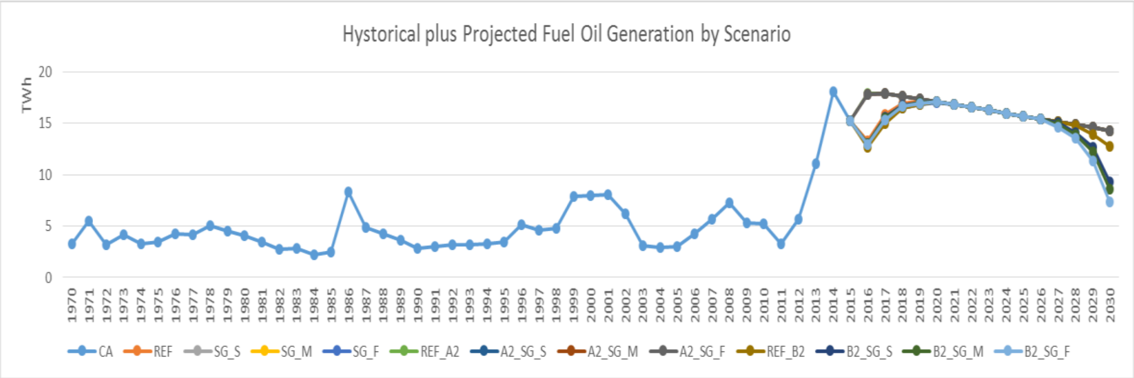


Figure 34: Historical plus projected fuel oil generation by scenario

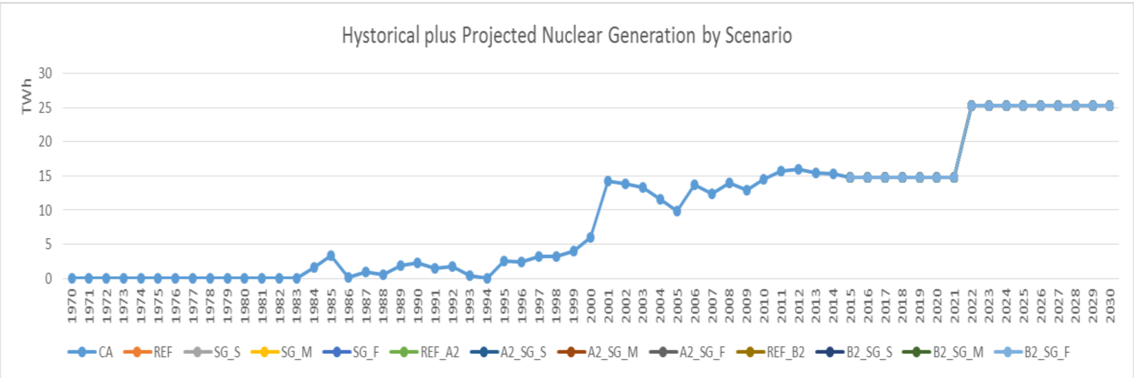


Figure 35: Historical plus projected nuclear generation by scenario

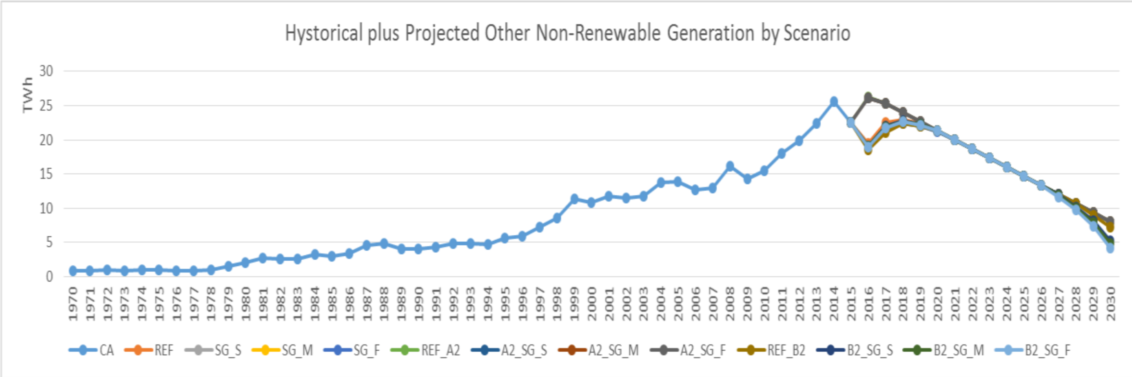


Figure 36: Historical plus projected other non-renewable generation by scenario

By the figures presented, one can see that some sources will have the same output no matter the scenario. Nuclear, for example, is better to keep producing as a base source than to use as back up. The same happened with solar and wind, as they generate electricity when have natural conditions. Otherwise, hydro will suffer from climate change and presents itself in two groups, as it was considering as a base source of energy.

According to the model projections, the coal, fuel oil and other non-renewable are expected to decrease. That was a positive result as in the national plan it is also expected to decrease but, with climate change effects and smart grids' impacts, the use was expected to decrease in a different speed.

Furthermore, natural gas is expected to increase, as related emissions are smaller for this source, as well as its maintenance and operation costs, when compared to other thermal concurrent.

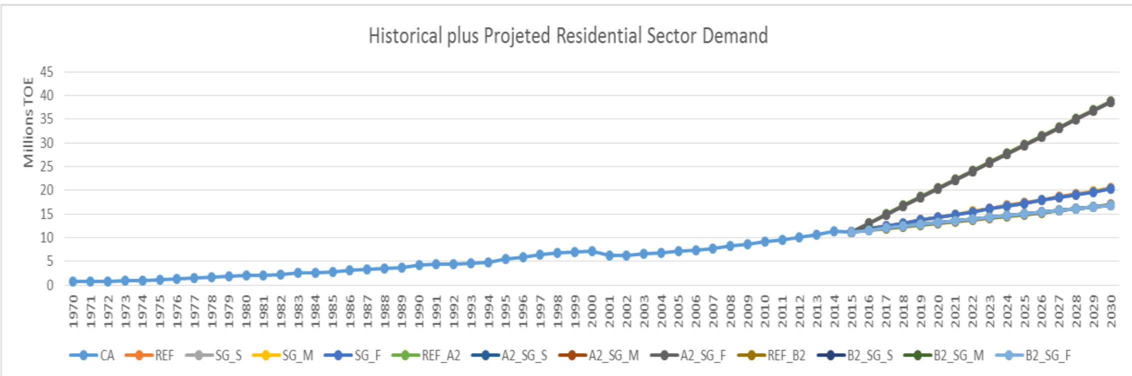


Figure 37: Historical plus projected residential sector demand

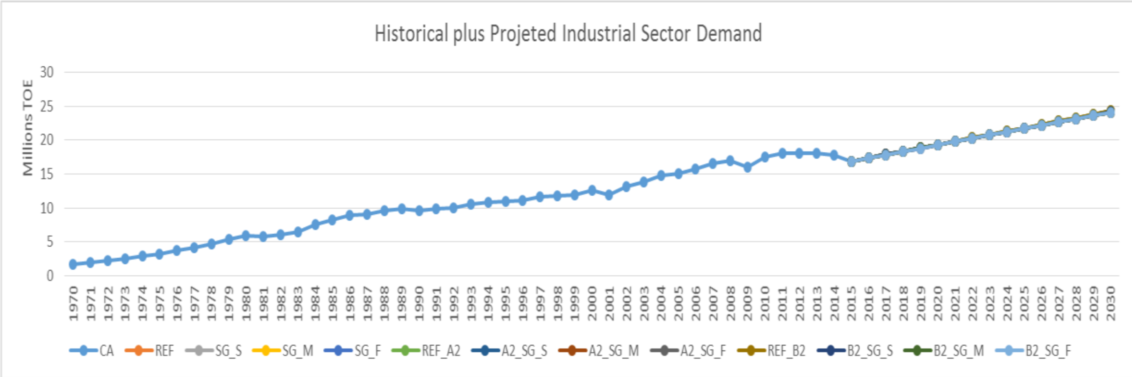


Figure 38: Historical plus projected industrial sector demand

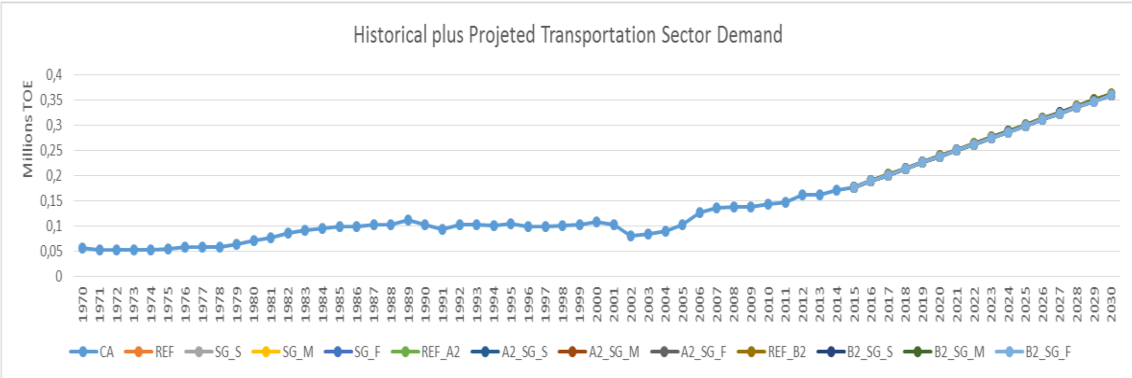


Figure 39: Historical plus projected transportation sector demand

In the transportation sector, it wasn't considered a big increase due to electric vehicles as Brazil is a leader in ethanol production and already has hybrid and 100% ethanol powered cars.

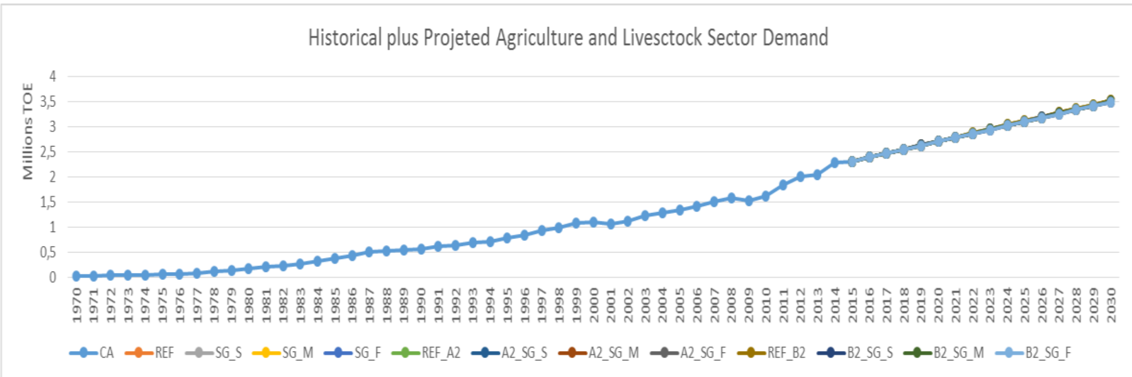


Figure 40: Historical plus projected agriculture and livestock sector demand

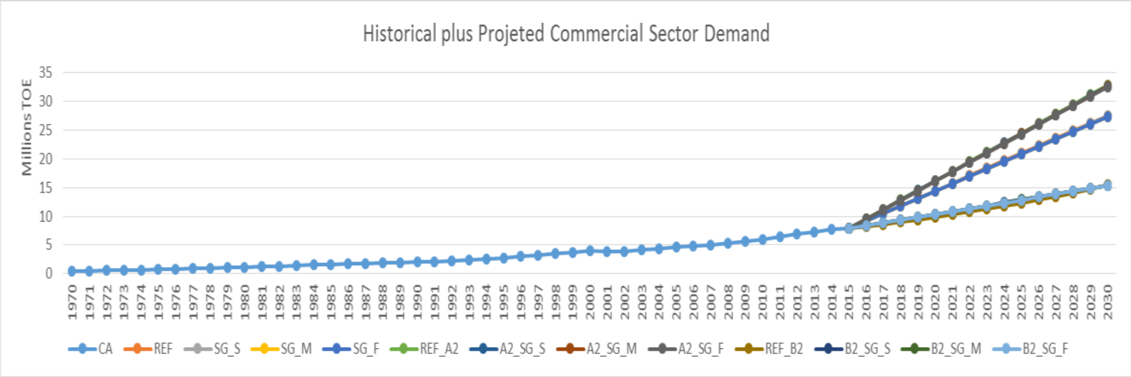


Figure 41: Historical plus projected commercial sector demand

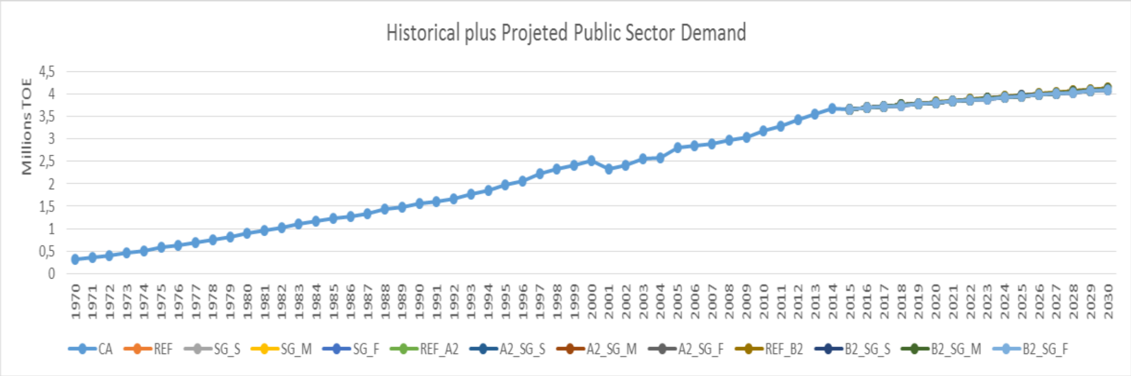


Figure 42: Historical plus projected public-sector demand

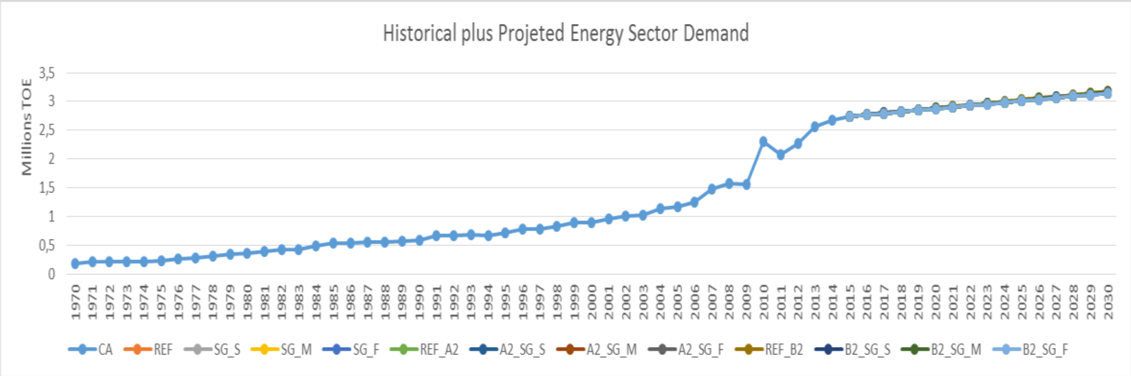


Figure 43: Historical plus projected energy sector demand

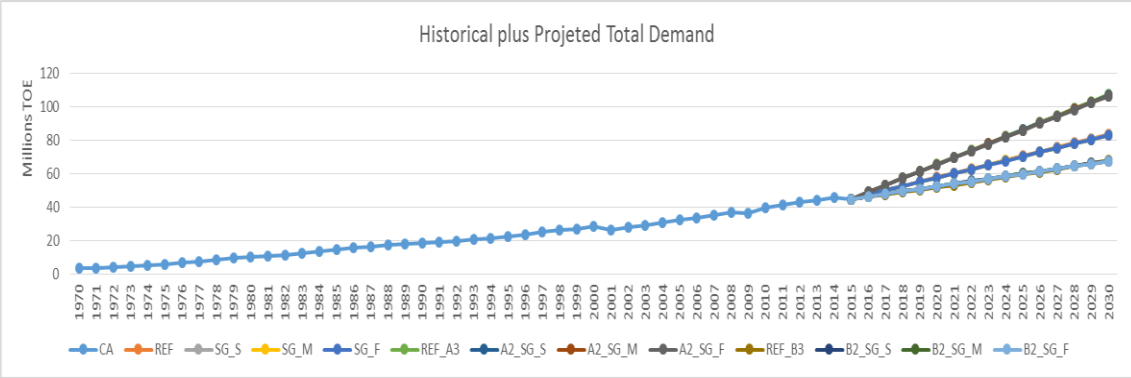


Figure 44: Historical plus projected total demand

As mentioned before, the projections for the demand only considered the effects of climate change on residential and commercial sectors demand for air conditioner and it created a limited area with A2 group as the worst scenario, B2 group as the best one and reference group in between.

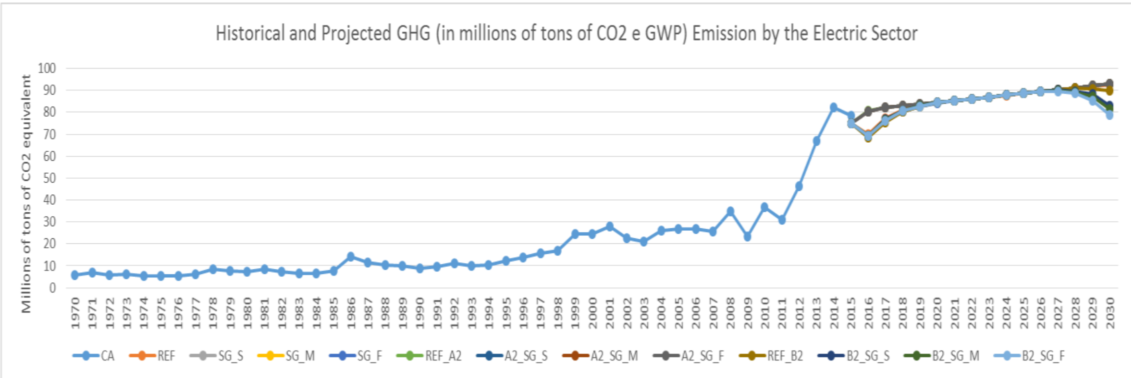


Figure 45: Historical plus projected GHG emissions

From Figure 45, one can notice that the GHG emissions are expected to be very similar during the first years, regardless the scenario (even in the reference group of scenarios where climate change effects are not considered, and hydro availability is higher). However, in the end of the analyzed period, i.e., when smart grids are expected to be fully integrated, the B2 group separate from the rest and start to decrease its emissions. Figure 46 seeks to highlight the difference between the scenarios presenting only the last five years of the projection period obtained with the use of the model.

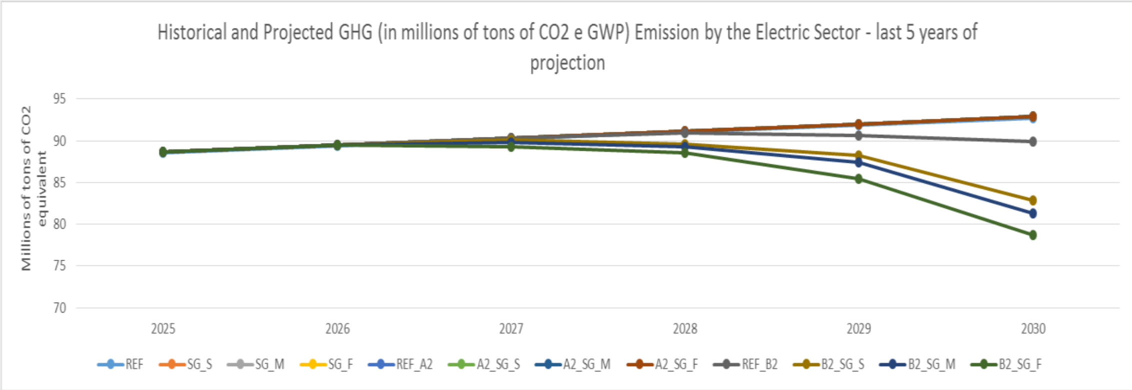


Figure 46: Highlight in the historical plus projected GHG emissions – between 2025 and 2030

The graphic in Figure 46 contains five lines: the three lines with lower emissions are the B2 group with smart grids; the fourth line with lower emission corresponds to the scenario B2 without smart grids; the top line is, in fact, six different scenarios overlapping, the reference group and the A2 group, with and without smart grids.

The last figure represents the capacity needed to attend the total demand but not dispatched.

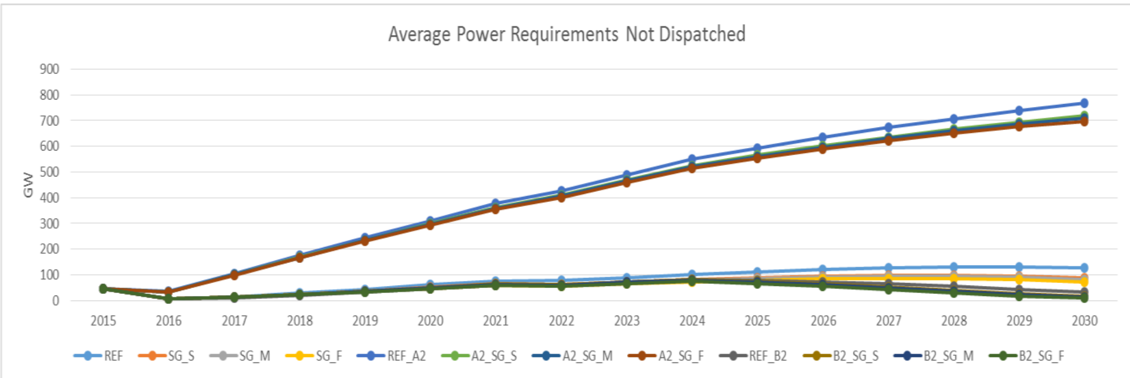


Figure 47: Capacity needed to attend the total demand but not dispatched

In this case, the result are two very different groups, where the A2 group has very high values when compared to the rest of scenarios.

Considering the equation presented by Sathaye and Ravindranath (1998):

CO2 emissions = population * GDP per capita[R$/people] * energy intensity[TWh/R$] * carbon intensity[$CO_2$/TWh]

When applied to this research it is possible to conclude that, based on Table 19:

Table 19: Results of Sathaye and Ravindranath Indicators for each scenario

	Energy intensity	Carbon intensity
CA	0,321	0,1288
REF	0,343	0,0892
SG_S	0,343	0,0892
SG_M	0,343	0,0892
SG_F	0,343	0,0892
REF_A2	0,295	0,1038
A2_SG_S	0,295	0,1038
A2_SG_M	0,295	0,1038
A2_SG_F	0,295	0,1038
REF_B2	0,296	0,0999
B2_SG_S	0,293	0,0933
B2_SG_M	0,292	0,0918
B2_SG_F	0,290	0,0892

When considering the indicator of nation's aggregate energy intensity, considering that there is no change in the composition of GDP, all changes observed in table are due to technology and efficiency. Therefore, as presented, only the B2 scenarios show an improvement in this indicator as it considers not only smart grid but also other technological changes to increase efficiency. The scenarios that only considers smart grids do not show any difference between the reference scenario and the smart grids scenarios (this difference appears in the energy needs for imports).

In what concerns the carbon intensity indicator, the same can be observed, only the B2 group of scenarios show any difference between the smart grids scenarios and the reference scenario.

Moreover, smart grids are also expected to reduce losses. Figures 48 to 50 presents the projected reduction for each scenario.

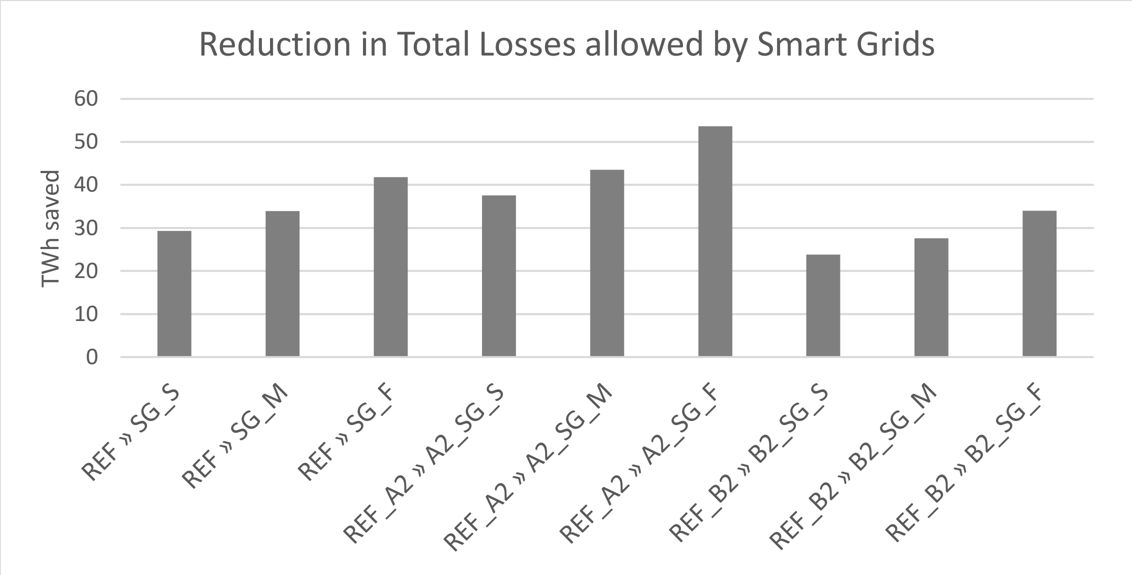


Figure 48: Technical and Non-Technical losses reduction

As expected, the smart grids help to reduce the losses, technical and non-technical, and Figure 48 presented the total losses reduction. In all scenarios groups the reduction, when compared to the reference climatic scenario from each group, increases with the increase in smart grids penetration.

Figure 49 shows losses monetization for the currently case and for the projected scenarios in 2030.

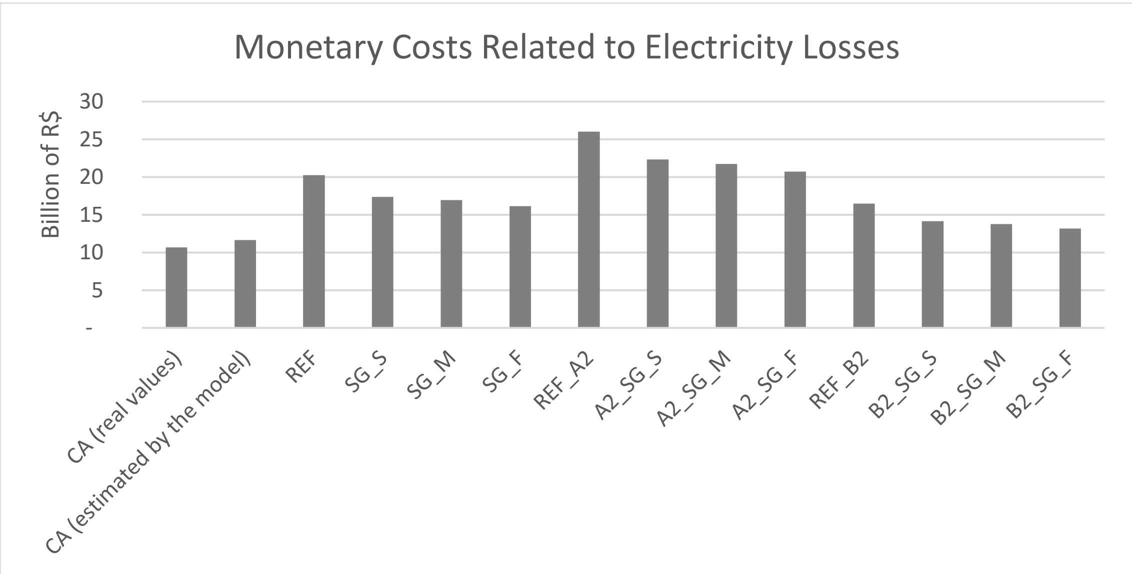


Figure 49: Monetary costs related to electricity losses by the use of smart grids

For a matter of comparison, Figure 49 presents two values for the current cost for electricity losses, the real value, presented by ANEEL (2016) and the values estimated using the model.

For the groups of scenarios, the costs decrease as the penetration of smart grids increase.

Figure 50 presents how much could be saved by implementing smart grids, comparing the expected losses from each smart grid scenario with its own reference scenario (how much would be lost in a reference scenario but could be saved by implementing smart grids technology).

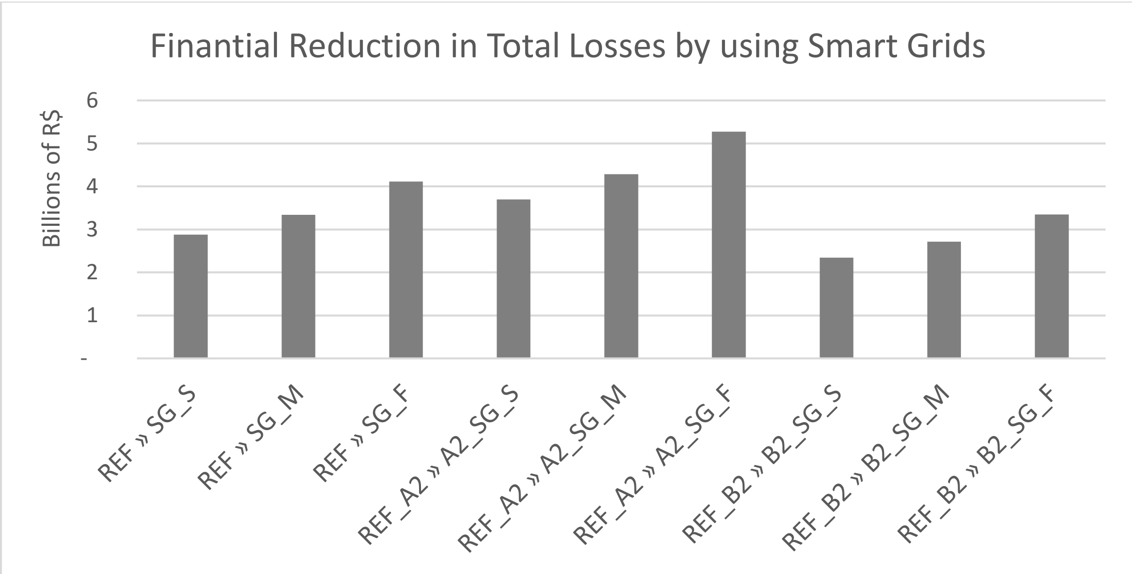


Figure 50: Total financial saved by using smart grids

As expected, as faster the implementation, higher would be the total amount of money saved by electricity distributions companies by using smart grids.

Furthermore, in what concerns the financial analysis, Figure 51 compares the costs of each reference scenario, costs for adding new installed capacity to attend the not dispatched electricity in 2030, to the same climate scenario with smart grids.

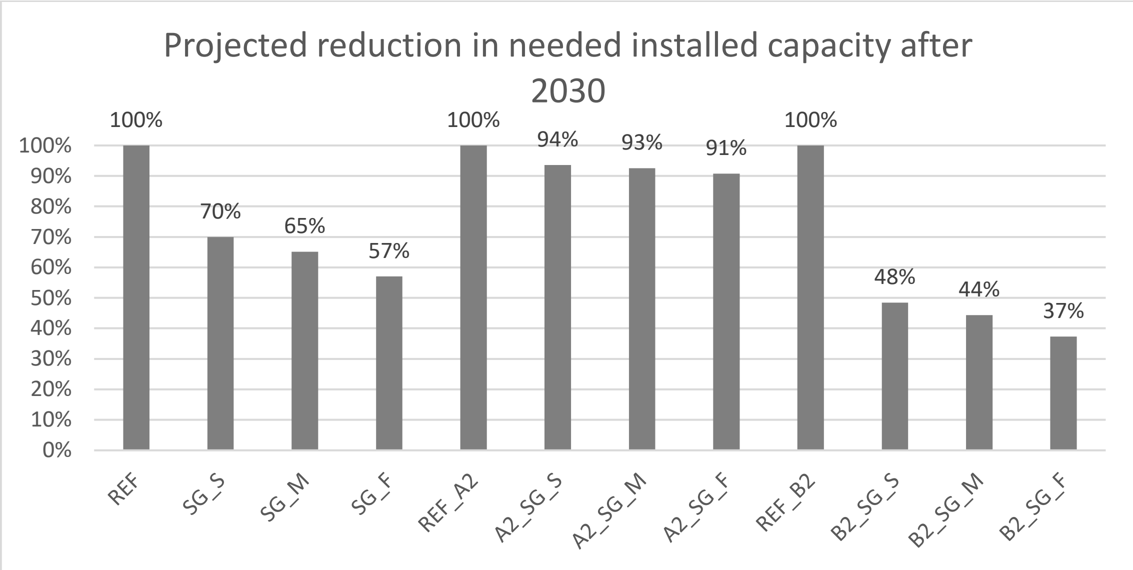


Figure 51: Projected reduction in needed installed capacity after 2030

Finally, Figure 52 shows the operation and maintenance costs for each scenario in 2030 according to the, already presented, installed capacity, generation mix, demand to be attended and expected losses.

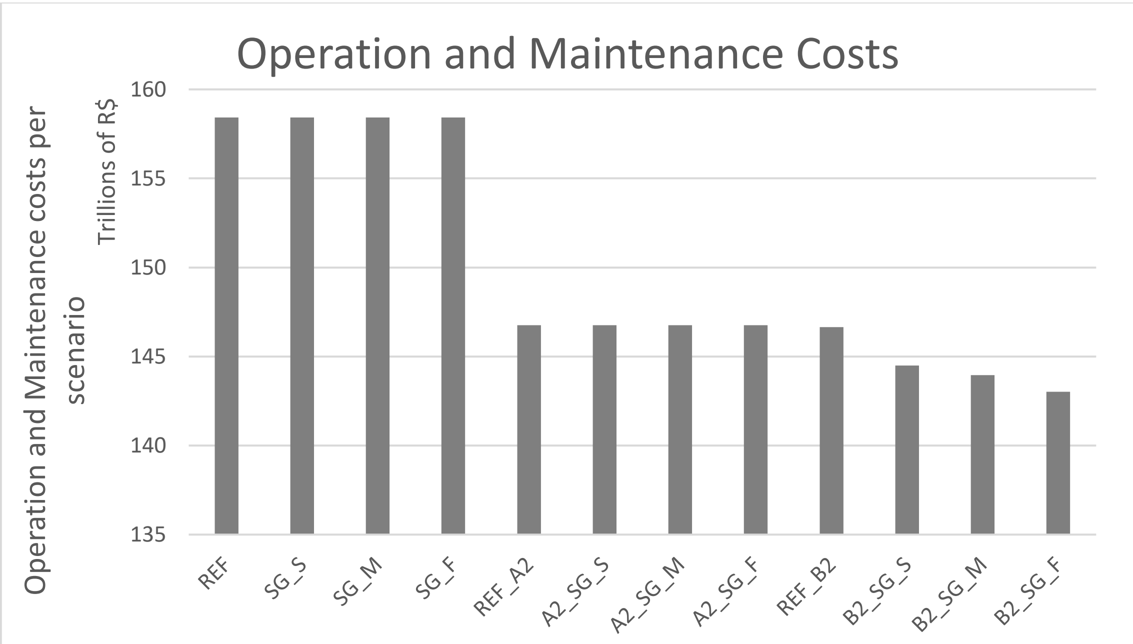


Figure 52: Projected OM costs in 2030

The operation and maintenance costs for the REF scenario group are the highest ones and the lowest one in the B2_SG_F scenario, while the A2 group stays in the middle.

Discussion

The results achieved with LEAP model shown that smart grids can help with climate change mitigation and adaptation, but these results are better when associated with a sustainable growth, i.e., change of obsolete domestic equipment for more efficient ones, changing lamps for others more efficient, changing electric shower for gas shower, etc.

Given the large hydro share, the energy sector in Brazil is not a sector with a large potential to reduce the GHG emission below the current level, i.e., presents a small mitigation capacity. However, it still need to adapt to future level of water available to generate electricity, in order to reduce the vulnerability of the sector. Nevertheless, the increase in renewable generation is not the only way to mitigate the energy sector; the consumption reduction and smart grid implementation can also contribute to this goal, not only by reducing the demand, but, especially, by reducing the losses.

Additionally, by reducing the losses (technical and non-technical), the electricity costs will also diminish, inducing tariffs decrease, as the final consumer pays for the losses.

Besides reducing the tariffs, another co-benefit from implementing smart grids is the creation of new industries, services and jobs as well as the increase in gross domestic product.

Even considering that Brazilian and EUA electricity mix are very different, it can be expected that smart grid could make the electricity sector more competitive and create new industries, services and jobs as pointed by Hamilton and Summy (2011).

It is important to keep in mind that the goal of this study was never to exactly predict the future of climate change or energy sector but to analyze, for different future probable scenarios, the impact of smart grids to mitigate and adapt the sector.

During this research, the power sector generation and consumption were characterized, the future of the sector, its vulnerability and the competitiveness of each source were addressed. The results presented by the LEAP model created showed that smart grids are able to contribute to increase the participation of renewable sources even with climate change conditions, especially solar and wind as the implementation of both sources suffers as the grid was not built to support them.

The intermittency of solar and wind sources requires a more robust system and smarter transmission lines. In Brazil the solar sources are mainly connected to the low voltage level (microgeneration); then, it affects the distribution system, as it has to adapt to thousands of micro generators sending energy to the network.

Furthermore, the wind energy has already started on a large scale in Brazil (it has been winning many energy auctions) and there is a challenge for the transmission industry to integrate an intermittent source that arrives on a large scale. The problem started when wind energy started to be introduced in Brazil as it was treated as an additional source (as the other sources used in the country – hydro with dam, thermal and nuclear) without considering the intermittency.

The simulation tests performed show that the best mitigation and adaptation results came from the B2 group of scenarios, which represent, not only the changes in climate, but also the changes in society (awareness about environmental issues, use of more efficient equipment, sustainable growth…)

Finally, smart grid would also help to reduce electricity tariffs by increasing the ability of the grid to take the most of Brazilian natural characteristics that gives the country great winds, insolation and water to small[13] power plants. The grid is not prepared to work with intermittent sources and domestic micro generation, so, smartening the grid would create the environment to helping use cheaper renewable energy, i.e., reduce the tariffs and walking, as close as possible, to a completely renewable system.

[13] There is a paradox involving hydropower, as there is some divergent opinion about how clean this source really is. The hydroelectric dams generate a surprising amount of greenhouse gas emissions, especially methane, and those gases are not accounted by global greenhouse gas inventories. CO2 and CH4 emissions from hydropower result from the oxic/anoxic decomposition of the flooded organic matter from different sources within the reservoir (e.g. vegetation and soils, macrophytes, and algae produced in the reservoirs) and from outside the reservoir (e.g. sedimentary OM input from the upstream river basin) (de Faria et al. 2015). In a research conducted by Faria et al. (2015) most of the simulated emission factors for Cachoeira dos Patos, Cachoeira do Caí, and Sinop are higher than those from thermal power plants. In Faria et al. (2015) research, they concluded that hydroelectric plants installed or planned to be built in the Amazon can be as or more polluting than thermoelectric plants. Eighteen new reservoirs could emit up to 21 million tons of methane and 310 million tons of carbon dioxide. As methane is 32 times more potent greenhouse gas than CO_2, the emissions can reach up to 982 million tons of CO_2e or, in a optimistic scenario, 369 million tons.

CHAPTER V: FINAL CONSIDERATIONS

Conclusion

This research presented an analysis of the potential of smart grid's technologies to mitigate and adapt the power sector to expected climate change. In order to achieve that, three groups of scenarios were considered: Reference, A2 and B2 scenarios, each one containing three levels of smart grid penetration, named as Slow, Moderate and Fast. Finally, an integrated model of the electric system was used to simulate the future generation for each scenario, the emissions and the impact of smart grid.

The presented approach was demonstrated by a case study in the power sector in Brazil, which differs from other countries power sectors because of large participation of renewable sources, mainly hydro and, as a consequence, a small potential to lower the current GHG emissions.

Thus, by considering the firm energy and capacity factor projection for the A2 and B2 scenarios, a model was created to simulate the future generation with the climate change impacts in temperature and precipitation. After that, mitigation scenarios were formed to simulate the demand, generation and GHG emission in the power sector. This analysis was based on the LEAP model. This model has some advantages when applied to the research in developing countries, as it has a low initial data requirement and those countries usually presents some lack of data. Nevertheless, it is also possible to add complexity only where data is available and where it provides further useful insights into the questions being addressed.

The results show that smart grids can help save energy by reducing losses in all climate scenarios. In the B2 group, smart grids can also contribute to mitigate the sector by reducing GHG emission, as this scenario also consider the use of more efficient equipment and a more conscious society. The A2 scenario presents a situation where the consumption is higher due to increase of number of hot days and temperature, which will increase the use of air conditioner in residential and commercial sectors. However, there is no large expected change for more efficient equipment and no awareness of the population (who stated in a ANEEL research on smart grid that "they do not know what it is, they are not interested in that and do not want to pay more to have it").

Additionally, the B2 scenario, even with a decrease in hydro generation, still having the least GHG emission, yet when compared to the reference scenario, which did not consider the climate change effects and still had a high hydro participation in 2030.

The smart grids also proved its potential to reduce the operational and maintenance costs and the investments in new power plants after 2030.

Recommendations and Future work

This research was focused on the SIN, which means the Brazilian national interconnected system, which covers almost the entire country. However, it would be interesting to analyze the impact, adaptation and mitigation measures within each region of the country (the regions could be the five geographical, the 4 SIN regions plus the isolated system or the basis regions) in order to adapt the solution to the characteristics and needs of each one. Brazil in a continental country and a general solution may not have the same impact/results in each region.

However, considering the particularities of the system, in some cases, a research focused on a particular power plant could be required.

Use of WEAP (Water Evaluation and Planning System), a tool created by Stockholm Environment Institute, which can help with integrated energy planning studies and could offer better results for Brazil as it operates on the basic principle of a water balance. It can simulate sectoral demand, water conservation, water rights and allocation priorities, surface flow and groundwater recharge from precipitation, reservoir operations, availability for hydroelectric power generation, Energy demands, pollution control of water quality, assessment of vulnerabilities and characteristics of aquatic ecosystems, and financial cost-benefit analyzes of projects. Finally, this tool helps on the establishment of preventive management strategies for the multiple use of water in several scenarios through the basic principle of water balance (LEAP and Ennergy Community n.d.).

A research on the acceptance of smart grids for consumers and the engagement of society on embracing a new technology and a new way to buy and use electricity would also be necessary as the B2 projections rely on, not only government, but the country engagement.

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Appendix A: Synthesis of the Energy Sector

This appendix synthetizes the main data on energy including energy production, by source, domestic supply, electricity generation and GHG emission.

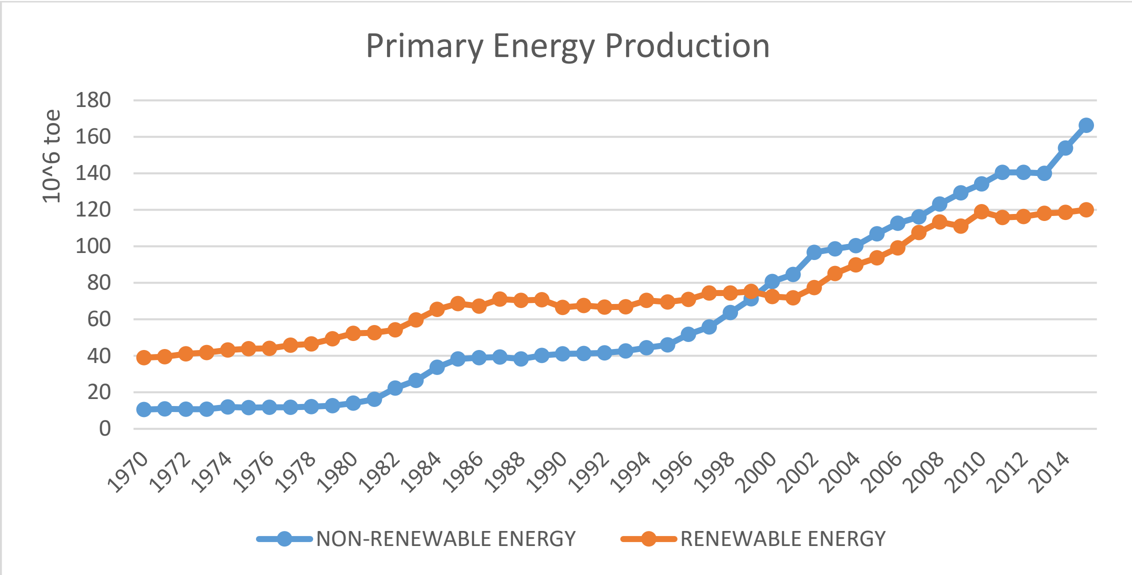


Figure 53: Primary Energy Production
Source: Data from BEN (EPE/MME 2016)

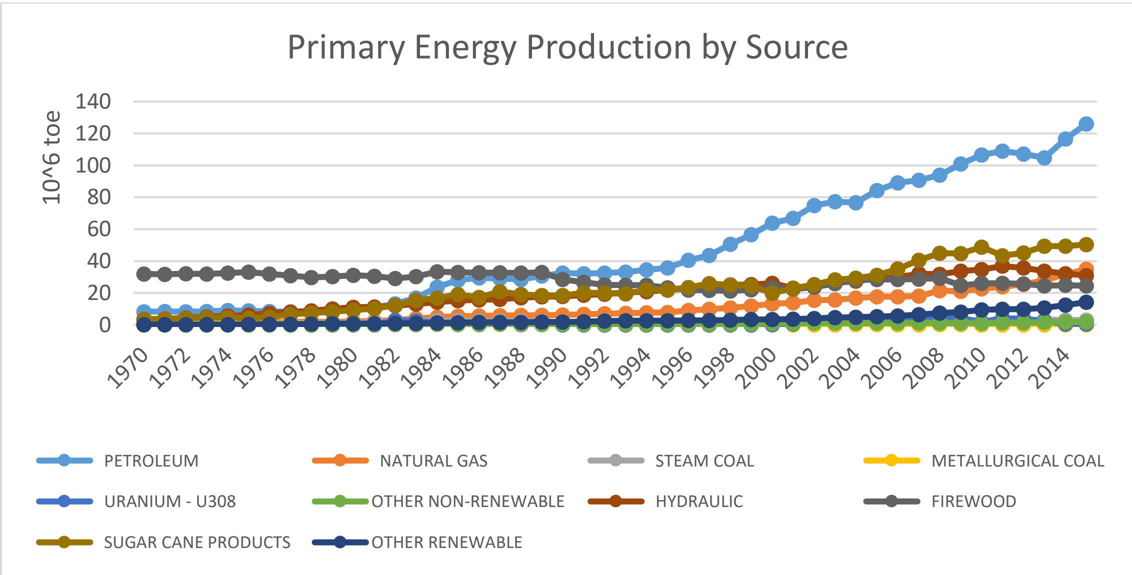


Figure 54: Primary Energy Production by Source
Source: Data from BEN (EPE/MME 2016)

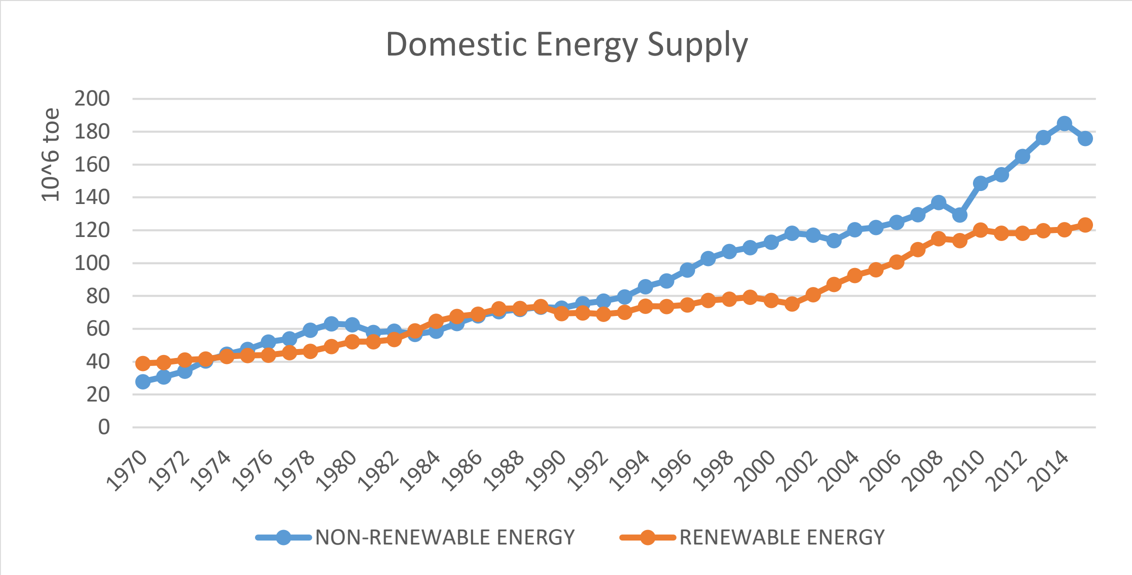


Figure 55: Domestic Energy Supply
Source: Data from BEN (EPE/MME 2016)

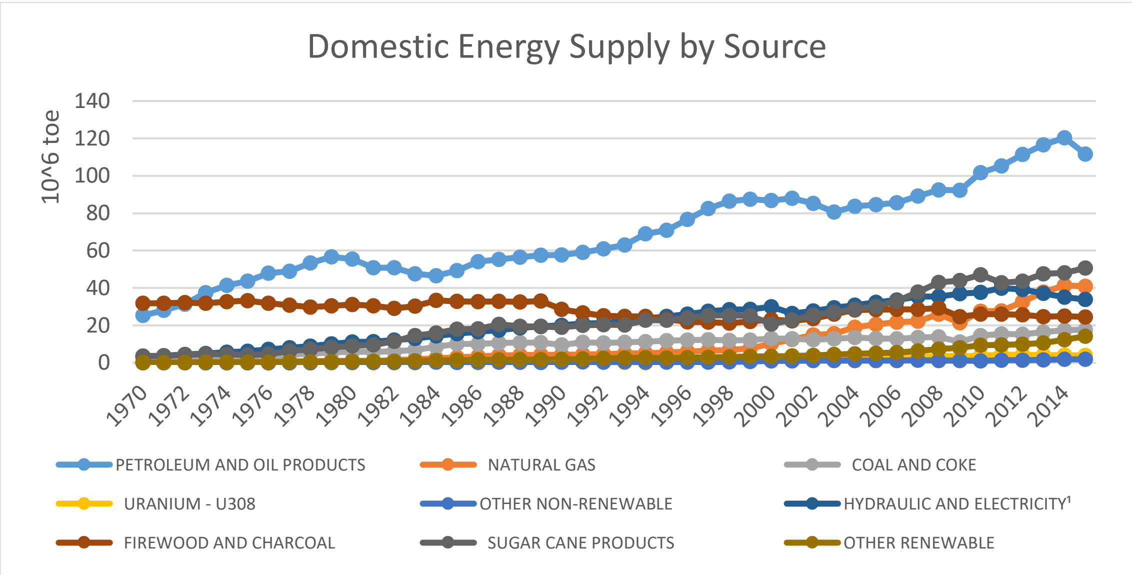


Figure 56: Domestic Energy Supply by Source
Source: Data from BEN (EPE/MME 2016)

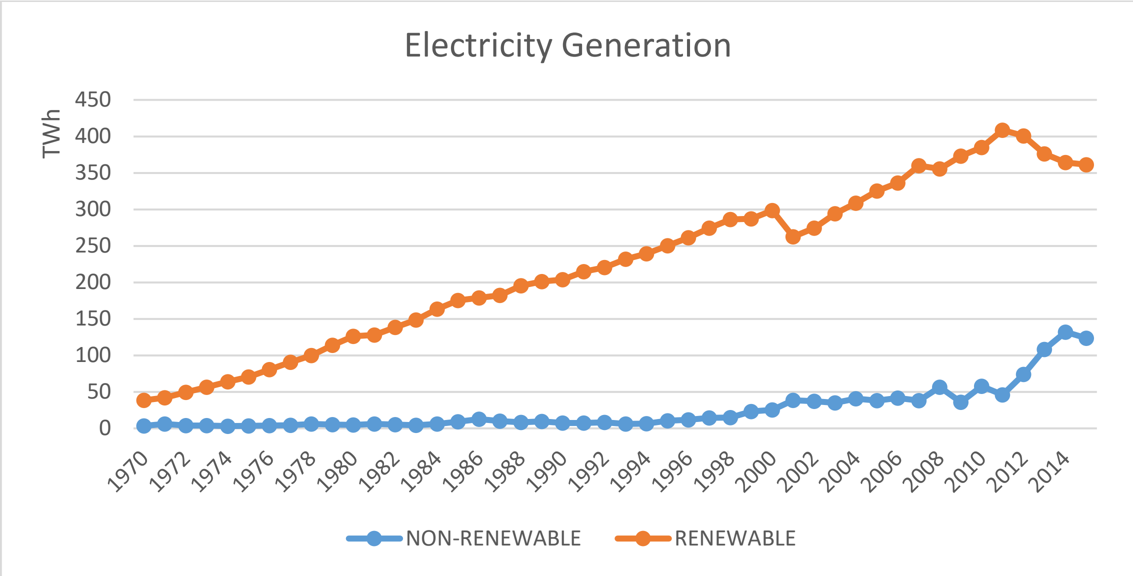


Figure 57: Electricity Generation
Source: Data from BEN (EPE/MME 2016)

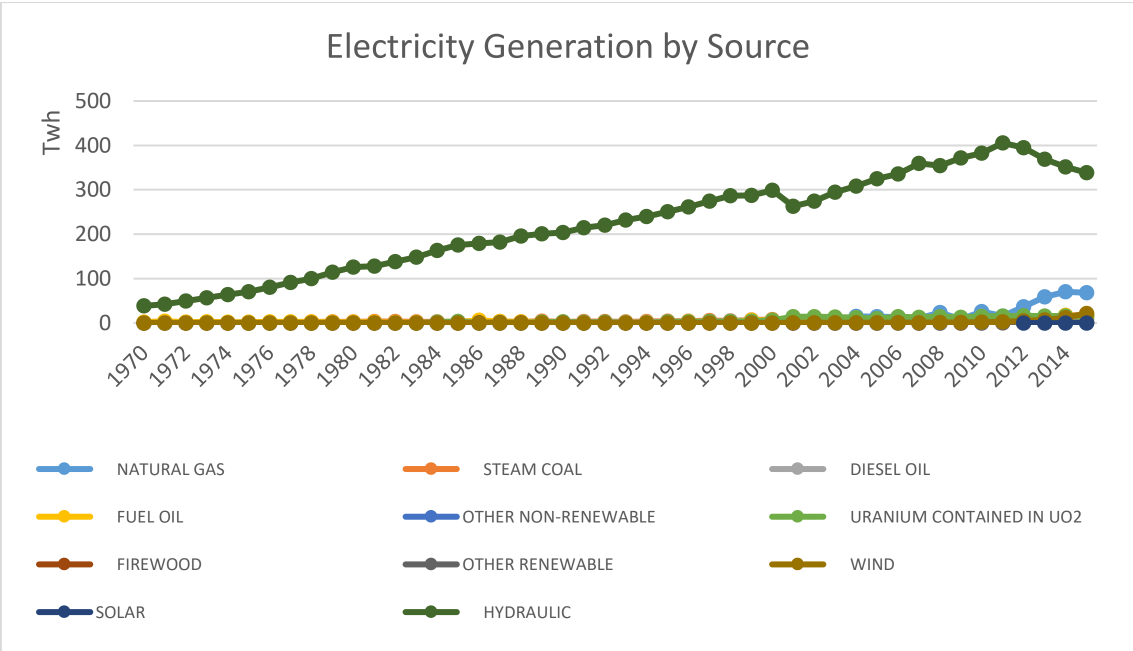


Figure 58: Electricity Generation by Source
Source: Data from BEN (EPE/MME 2016)

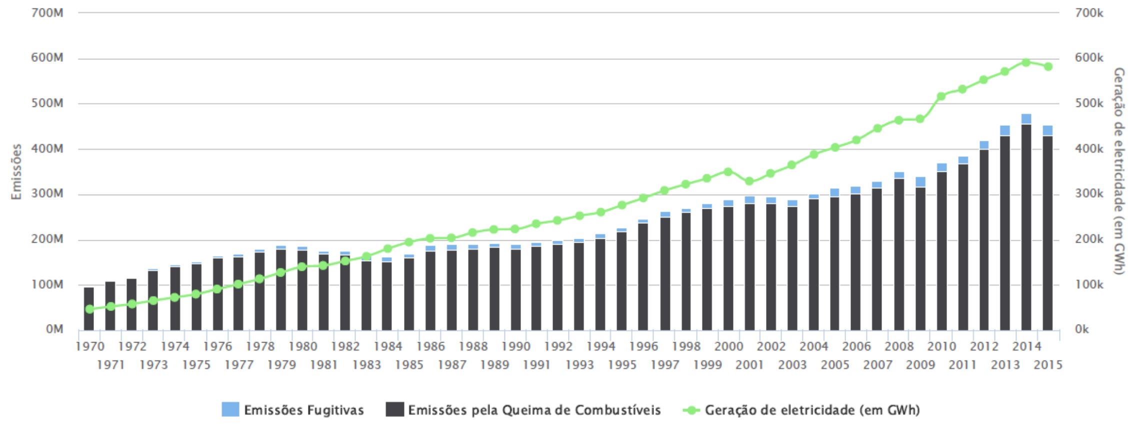


Figure 59: GHG emission by electricity sector compared with electricity generated
Source: Data from BEN (EPE/MME 2016)

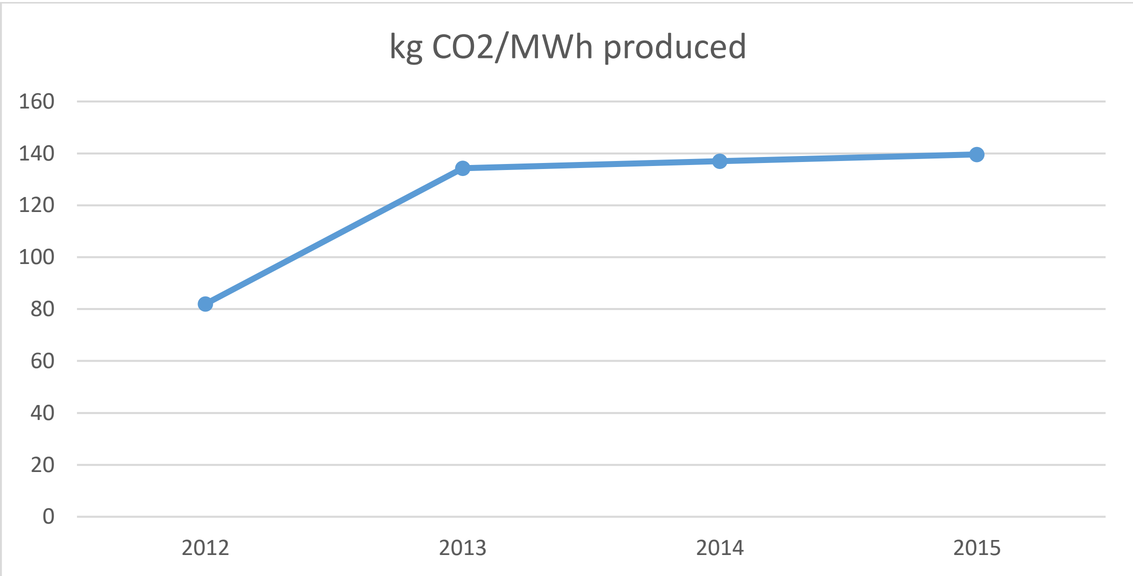


Figure 60: kg of CO2 emitted by MWh produced
Source: Data from BEN (EPE/MME 2016)

Appendix B: Evolution of the Brazilian Power Sector: data analysis

Installed Capacity

The installed capacity can be seen as the maximum amount of electric energy that can be produced in the country considering the best conditions scenario.

In order to better understand the graphics that will be presented some issues must be clarified:

- The hydro installed capacity incudes half of Itaipu Power Plant (the Brazilian part of the binational hydro power plant);
- IEP stands for Independent Energy Producers;
- IEP plants, traditionally self-producers (SP), are classified as SP[14];
- Solar corresponds to photovoltaic energy;
- PU is a reference for public utilities power plants.

First of all, Figure 61 presents the installed capacity by producer type (PU or SP).

[14] IEP and SP are treated as different things but, in reality, this difference is very tenuous. SP and IEP are defined as being: (1) Independent Energy Producers are legal entities or companies in a consortium that receive a concession or authorization to produce electricity destined to trade in all or part of the energy produced at their own risk; (2) Self-Producers are natural or legal persons or companies that are members of a consortium that receive a concession or authorization to produce electricity for their exclusive use, and may, with authorization from ANEEL, sell the surplus electric power generated. Traditionally, the self-producer was a consumer who owned plants to generate his own energy and could market the surplus. The concept of independent producer came with more possibilities of commercial arrangements. Both are considered self-producers but can legally be authorized as self-producers or as independent producers(Energybras - Energias Renováveis n.d.).

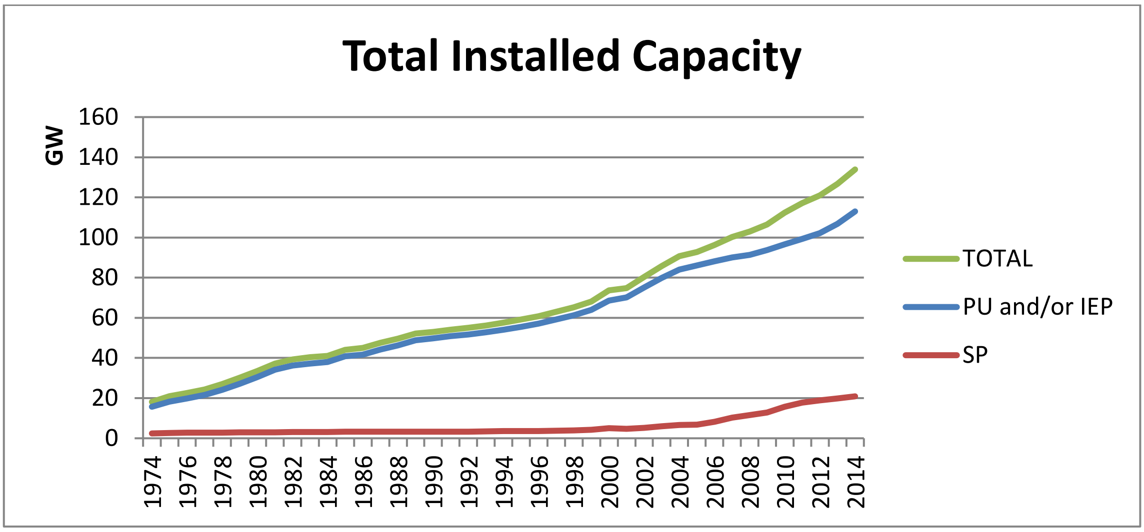


Figure 61: Total PU, IEP and SP installed capacity from 1974 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

It can be seen that the PU are responsible for the majority of the installed capacity in the country, however, the SP are increasing its participation since 2000, and more especially 2005, the period of model transition in Brazil.

Figures 62 to 67 presents the same information as Figure 61 but separated by source of energy.

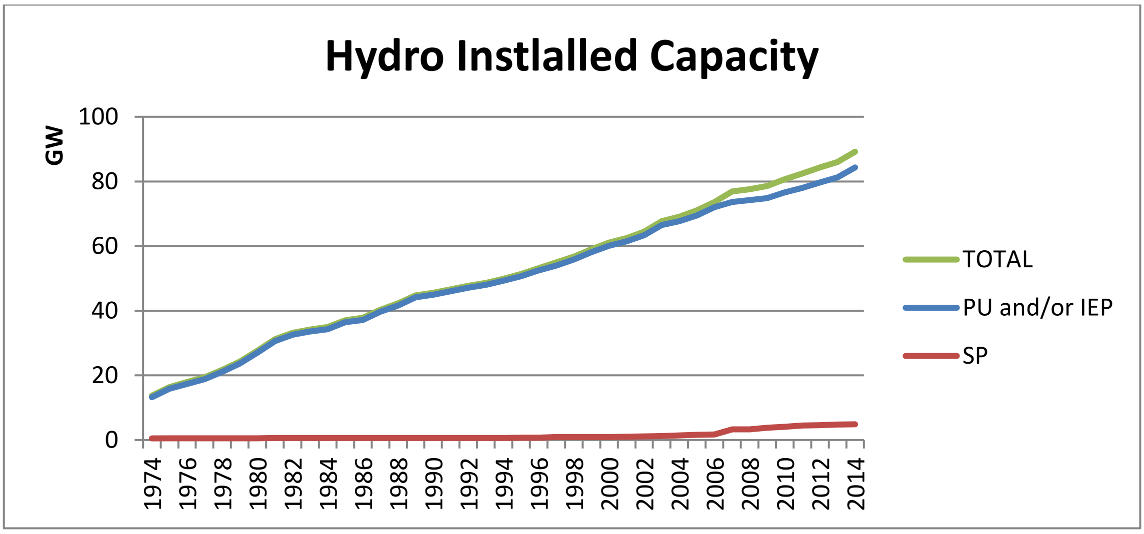


Figure 62: Hydro installed capacity from 1974 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

Figure 62 shows that PU play an important role in the hydro installed capacity as it is almost all from public utilities.

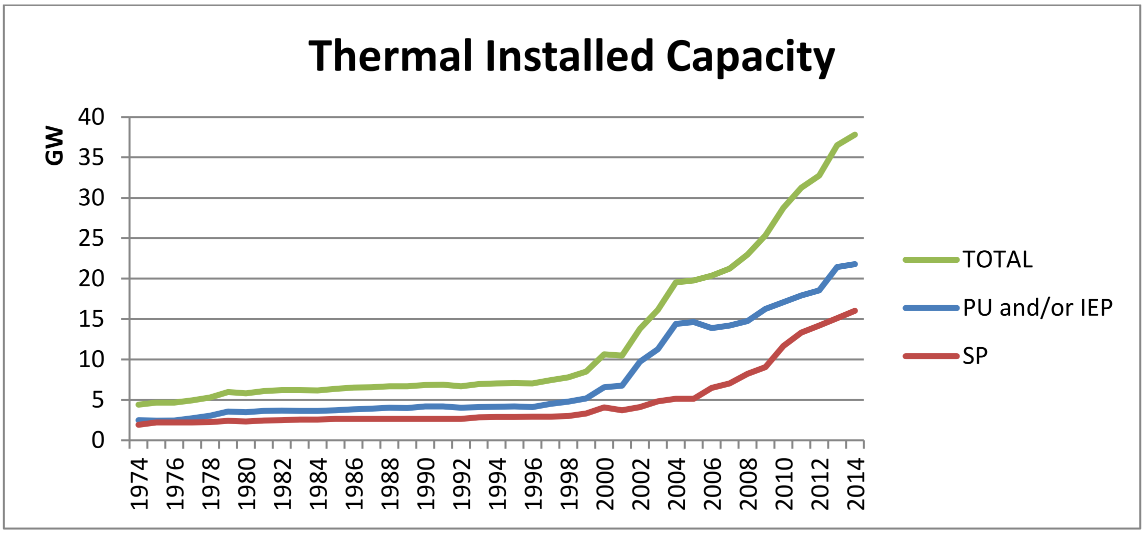


Figure 63: Thermal installed capacity from 1974 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

Figure 63 shows that PU and SP are not very distant in the participation in thermal installed capacity.

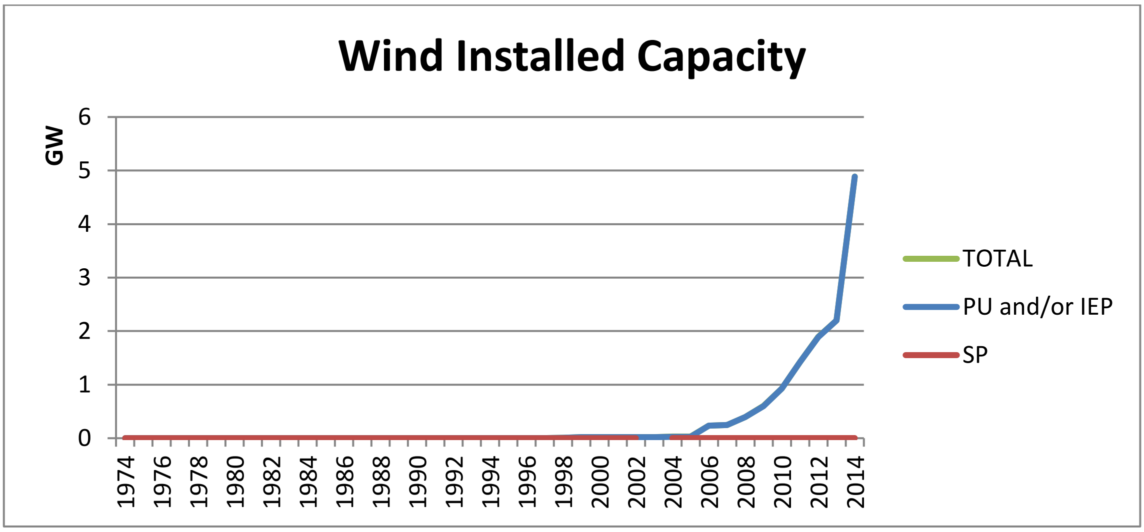


Figure 64: Wind Installed capacity from 1974 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

In what concerns about wind installed capacity, Figure 64 shows that it is almost only PU.

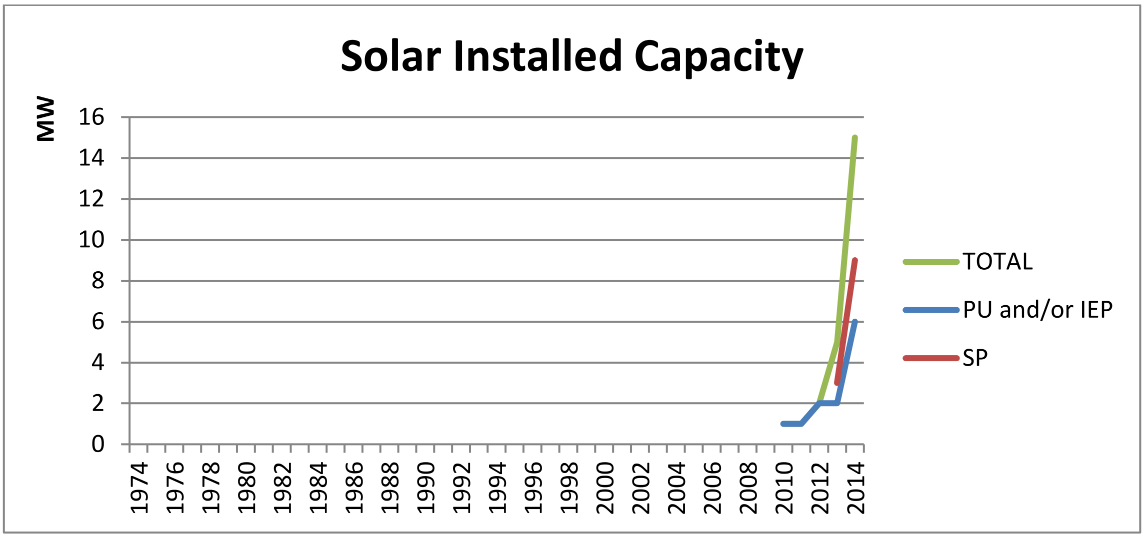


Figure 65: Solar installed capacity from 1974 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

The solar installed capacity still very recent in the country and its small installed capacity have not a big difference in participation when comparing PU and SP.

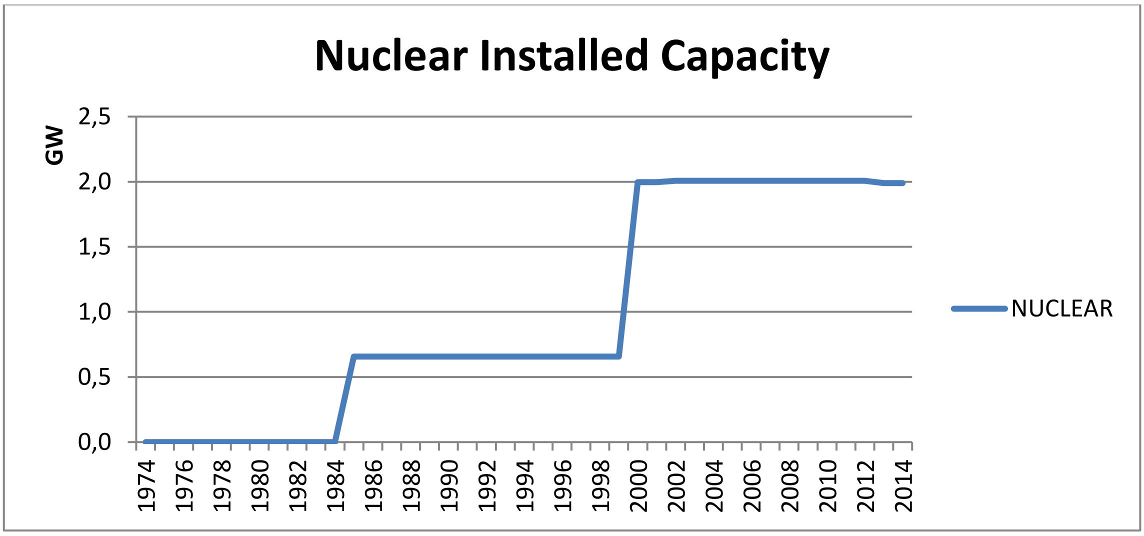


Figure 66: Nuclear installed capacity from 1974 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

Finally, the nuclear installed capacity, which is all PU and represents the two nuclear power plants in Brazil.

The next figure, Figure 67, presents the total installed capacity in Brazil but its data is divided by source in order to see the importance of each source for the national electric energy mix.

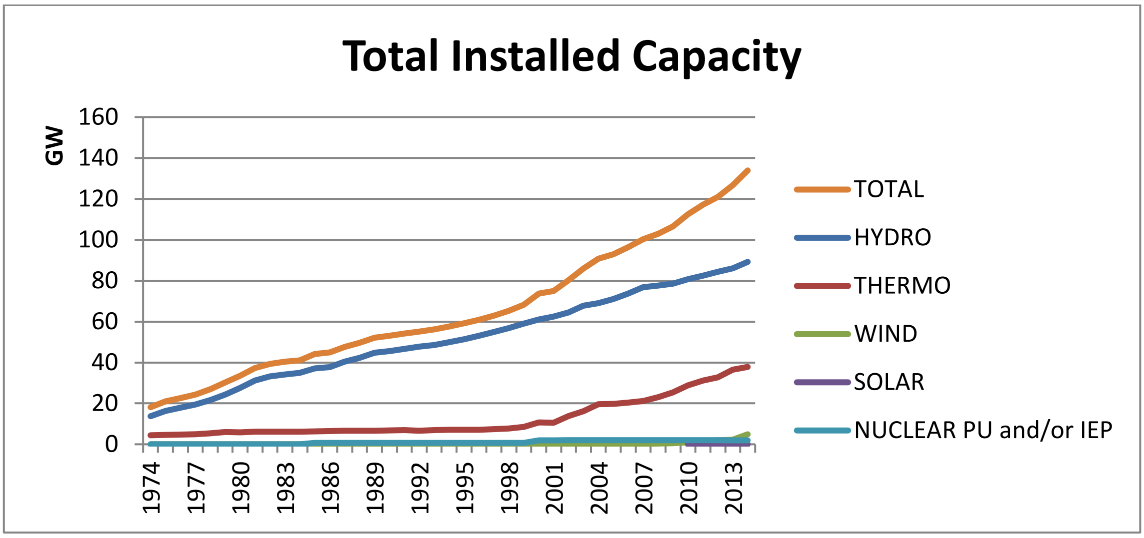


Figure 67: Total installed capacity by source from 1974 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

From Figure 67 and from the first sector of this report it is possible to confirm that the hydro source is the main source of electric energy in the country followed by thermals, which assures the security of supply in a water scarcity scenario. It is also possible to see that thermal installed capacity participation is growing faster since 2001.

Figure 68 and 69 presents the participation of each source of electricity in the installed capacity of each kind of producer.

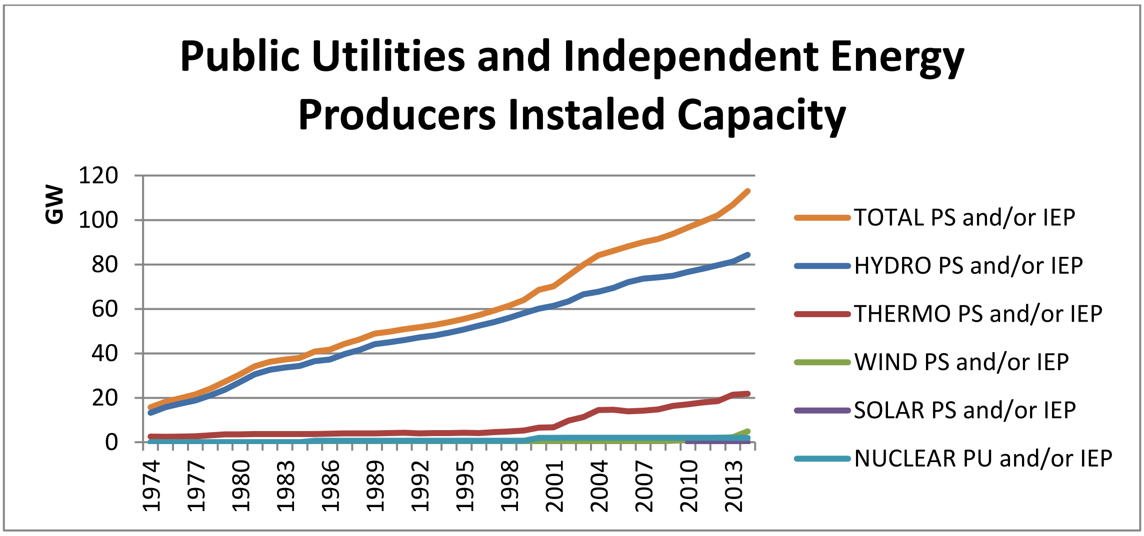


Figure 68: PU and IEP installed capacity by source from 1974 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

The configuration of Figure 68 is not very different of the previous one because of the huge participation of PU compared to SP, which could be seen in Figure 61.

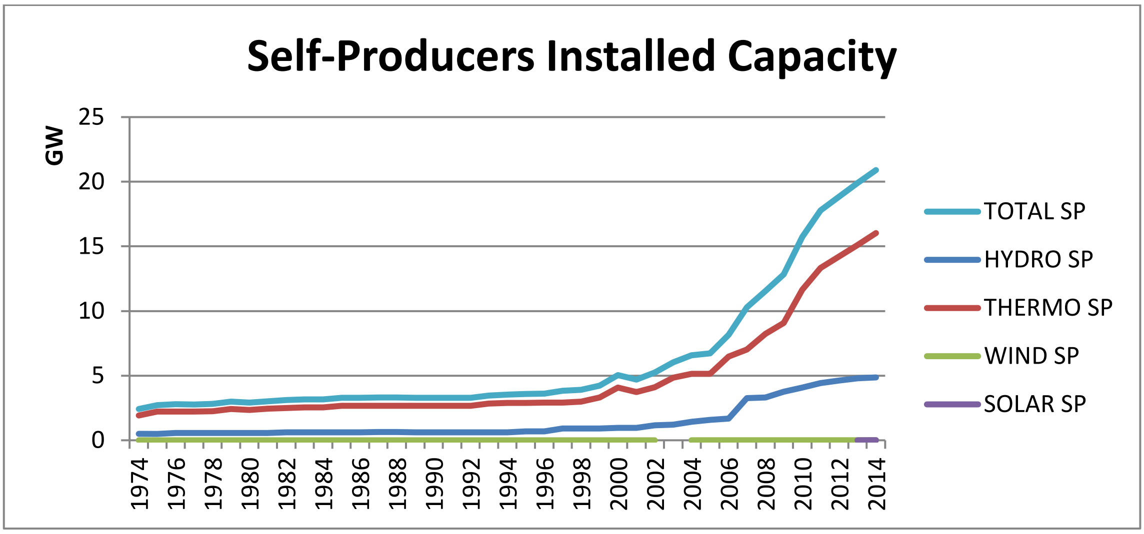


Figure 69: SP installed capacity by source from 1974 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

When analyzing only the SP installed capacity the situation is very different with predominance of thermals followed by distance for hydro installed capacity which only started to grow after 2006.

Now that an overview of the installed capacity was presented, the next point addresses the generation.

Generation

In this section the generation corresponds to the total energy produced in the country in each year and the input (fuel for thermal power plants) necessary to produce it.

First, one aspect to be considered is the shape of the load in the country. Figure 70 presents the evolution of the daily load curve of the SIN during the summer and winter periods, between 2000 and 2014.

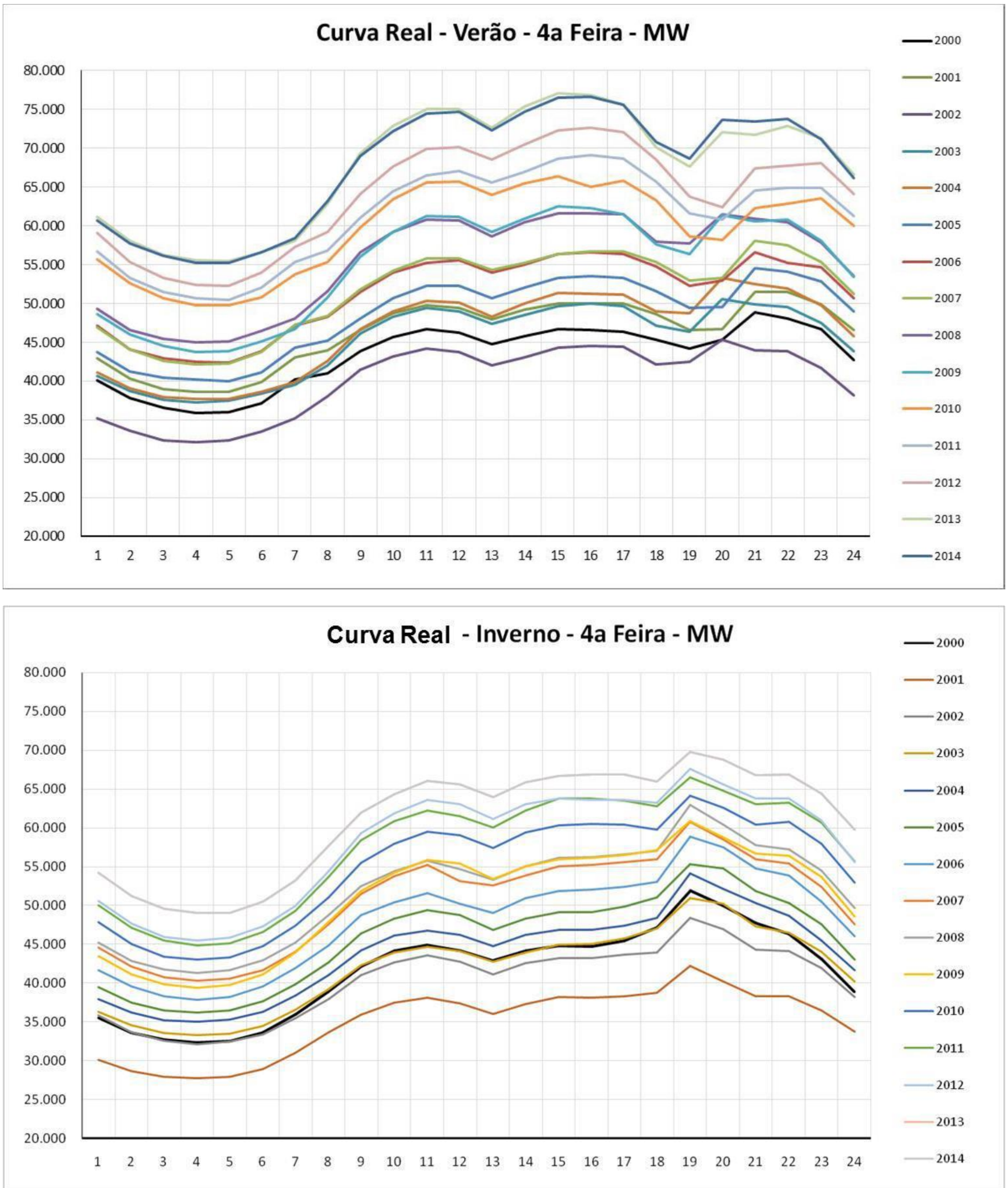


Figure 70: Evolution of the daily Load Curve of the SIN in Wednesdays during the summer (left) and winter (right) from 2000 to 2014 in MW
Source: EPE/MME 2015

The analysis of these curves indicates that the consumptions during summer and winter are different: the peak, during the winter is around 7pm but during the summer is more often between 3pm and 4 pm. Several factors contribute to this difference like the increase in air conditioning equipment in the residential and commercial sectors, the management of cargo at classic rush hour, changes in the [end] expedient of the commercial sector and some industries, public lighting and, of course, increased distributed generation operating at peak hours (EPE/MME 2015b).

The first figure, Figure 71 represents the yearly total input used by public utilities (PU) power plants, from 1970 to 2014, to generate electric energy.

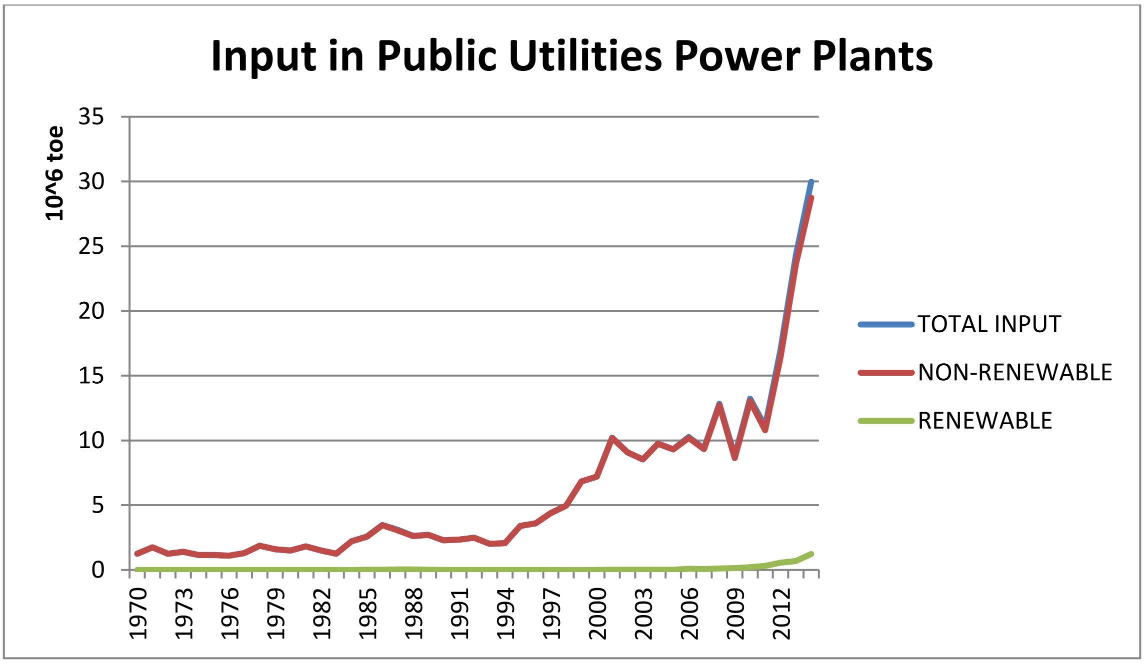


Figure 71: Input in PU power plants from 1970 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

Figure 71 shows that the input is mainly non-renewable, the use of renewable ones only started to grow after 2010 and its participation still very insignificant.

Figure 72 represents the participation of each non-renewable source in the total non-renewable input.

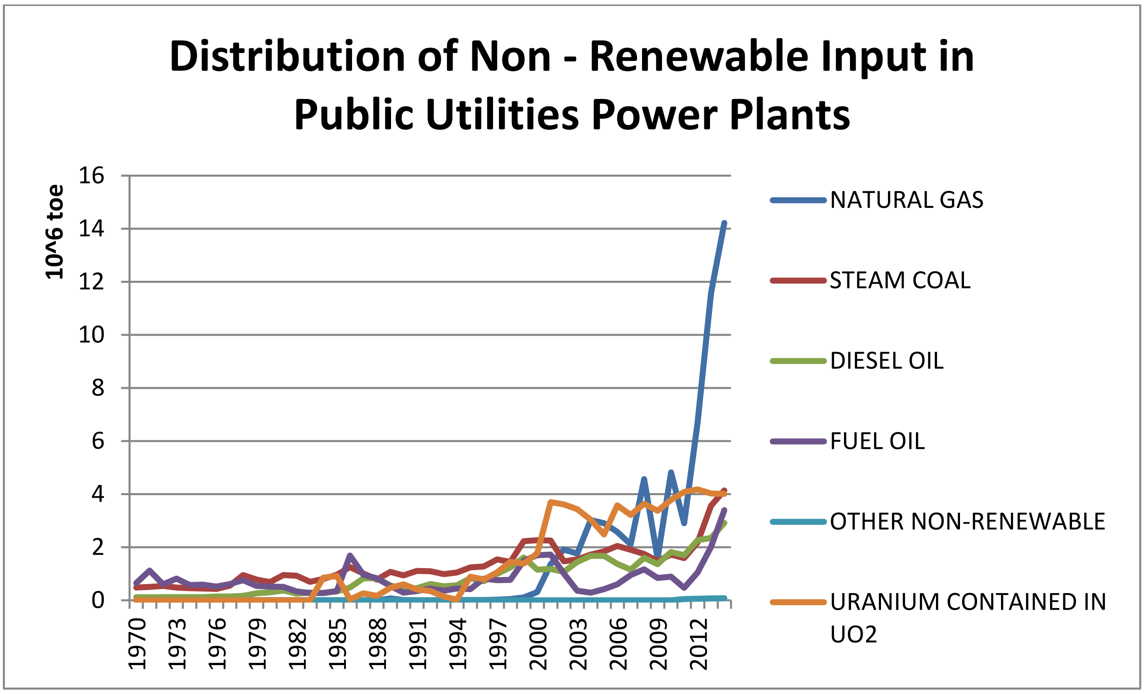


Figure 72: Non-Renewable input in PU power plants from 1974 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

Figure 72 shows that until the year of 2011 the participation of each non-renewable input was, more or less, the same. However, after that the natural gas gained much more importance for the electricity generation in thermal power plants.

Figure 73 represents the participation of each renewable source in the total renewable input.

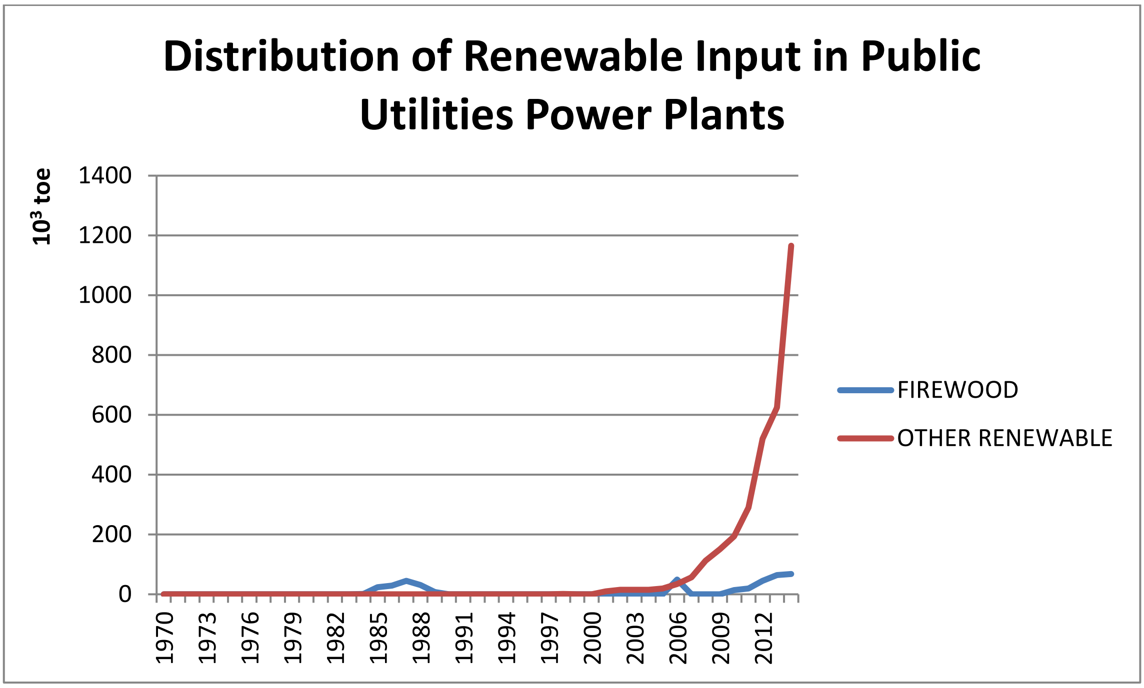


Figure 73: Renewable input in PU power plants from 1974 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

When considering the renewable input, Figure 73 shows that firewood is the only significant source used, even knowing that the others added up represents much more than firewood, each one of them, separately, are not significant.

In what concerns the energy generated, Figure 74 presents the total amount of electricity generated by hydro PU and thermal PU.

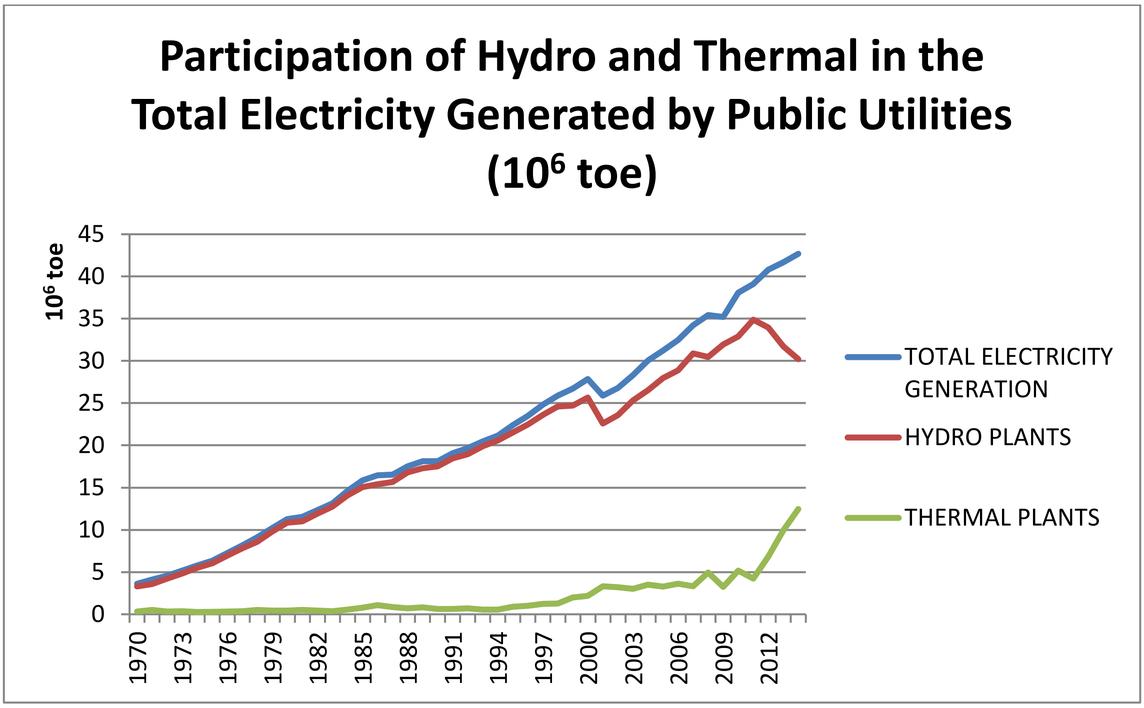


Figure 74: Participation of hydro and thermal in the PU total generation from 1974 until 2014 – 10^6 toe
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

From Figure 74 it is possible to see that when the total hydro generation has been decreasing, the total thermal generation is growing, especially after 2011.

The next graphic, Figure 75, presents the total losses by the PU thermal plants.

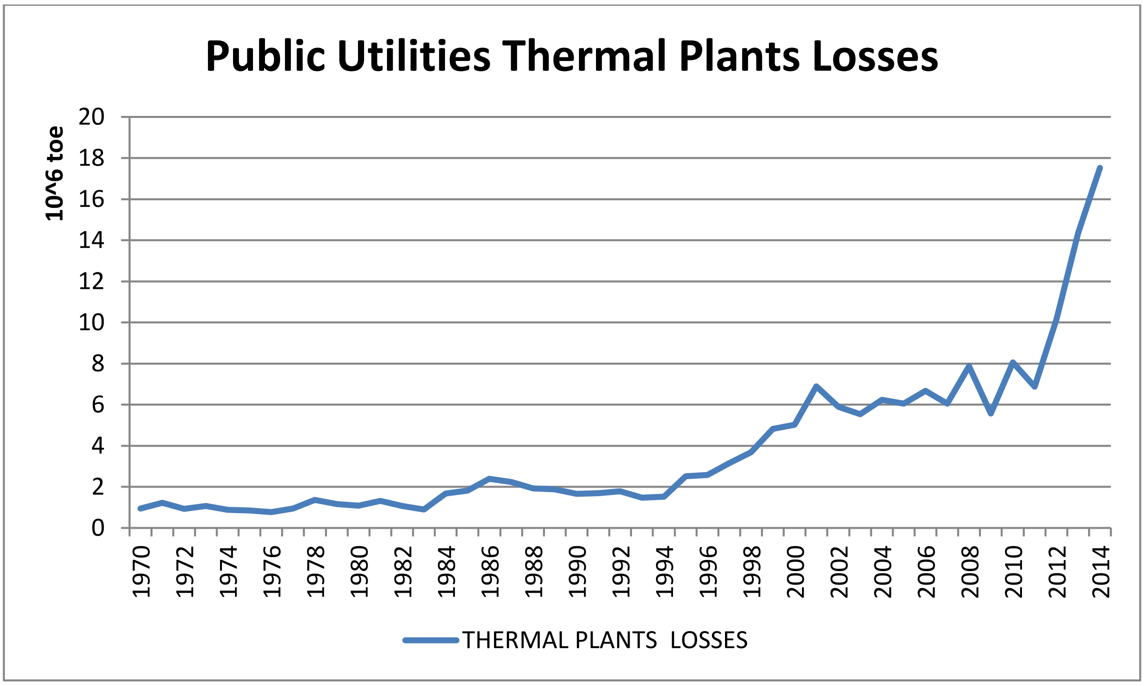


Figure 75: Losses in PU thermal plants from 1970 to 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

From Figure 75 it is possible to see that the losses have been increasing fast since 1994 and especially after 2011.

Figure 76 shows the average efficiency of PU thermal plants, per year.

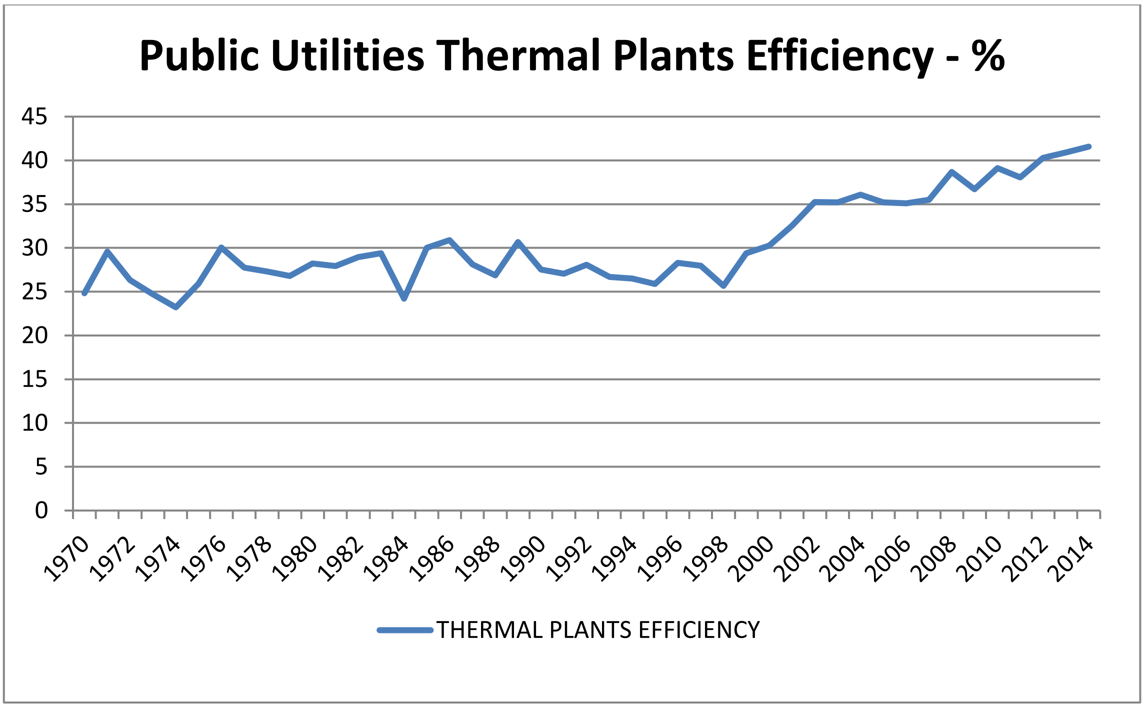


Figure 76: Percentage of the PU thermal plants efficiency from 1970 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

Figure 76 shows that the efficiency of the thermal power plants is increasing since 1998, even considering the increase in losses.

Figure 77 presents the participation of renewable and non-renewable sources in the total electricity generated yearly.

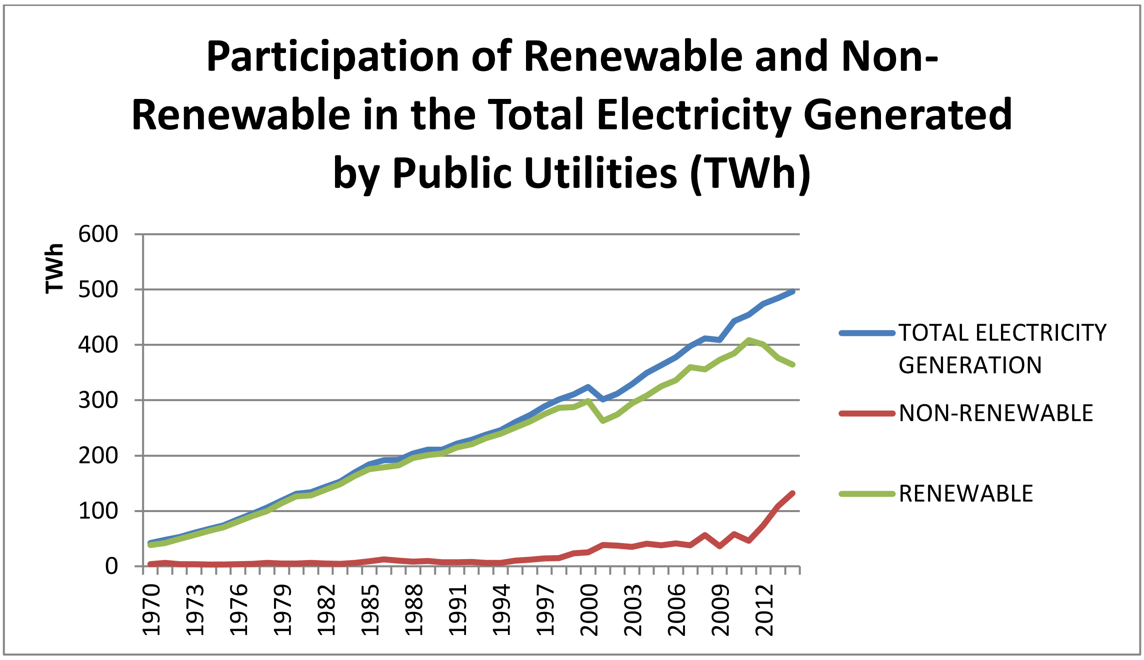


Figure 77: Participation of renewable and non-renewable in the PU total generation from 1974 until 2014 – TWh
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

As the renewable generation in mainly hydro and the non-renewable is mainly thermal, there is no big difference between Figures 77 and 74.

Figure 78 and 79 presents the participation of each non-renewable and each renewable source in the total non-renewable and total renewable generation, respectively.

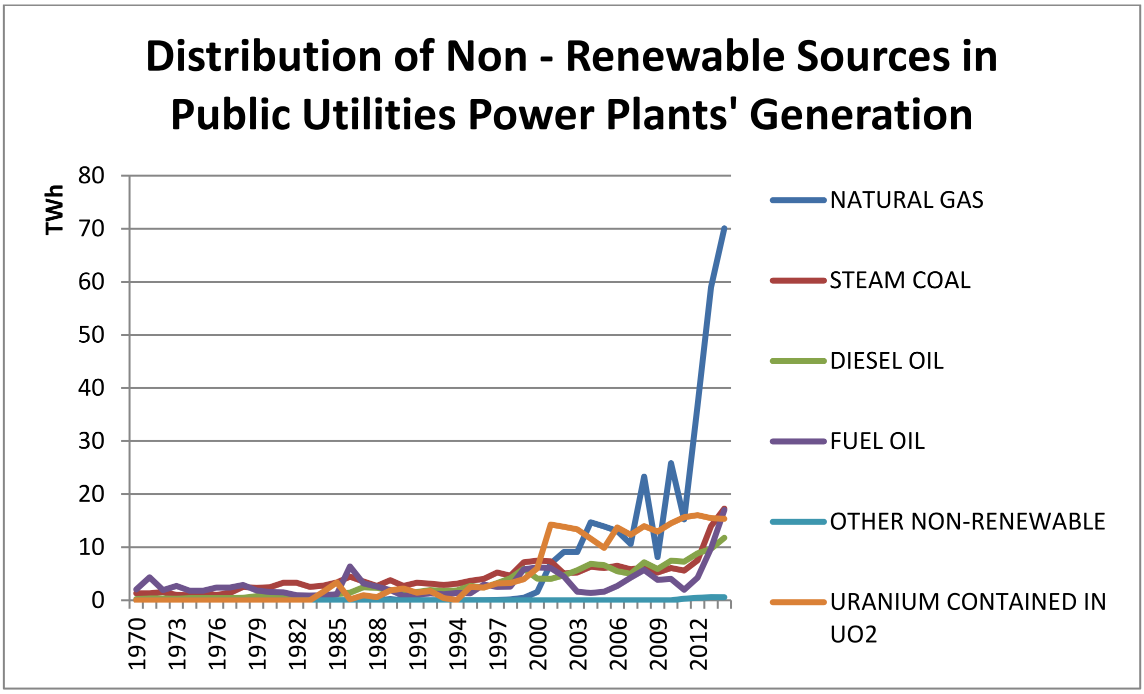


Figure 78: Generation by each non-renewable source in PU from 1970 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

Figure 78 reflects the information presented in Figure 72, and the natural gas, after 2012, plays the main role in the non-renewable generation.

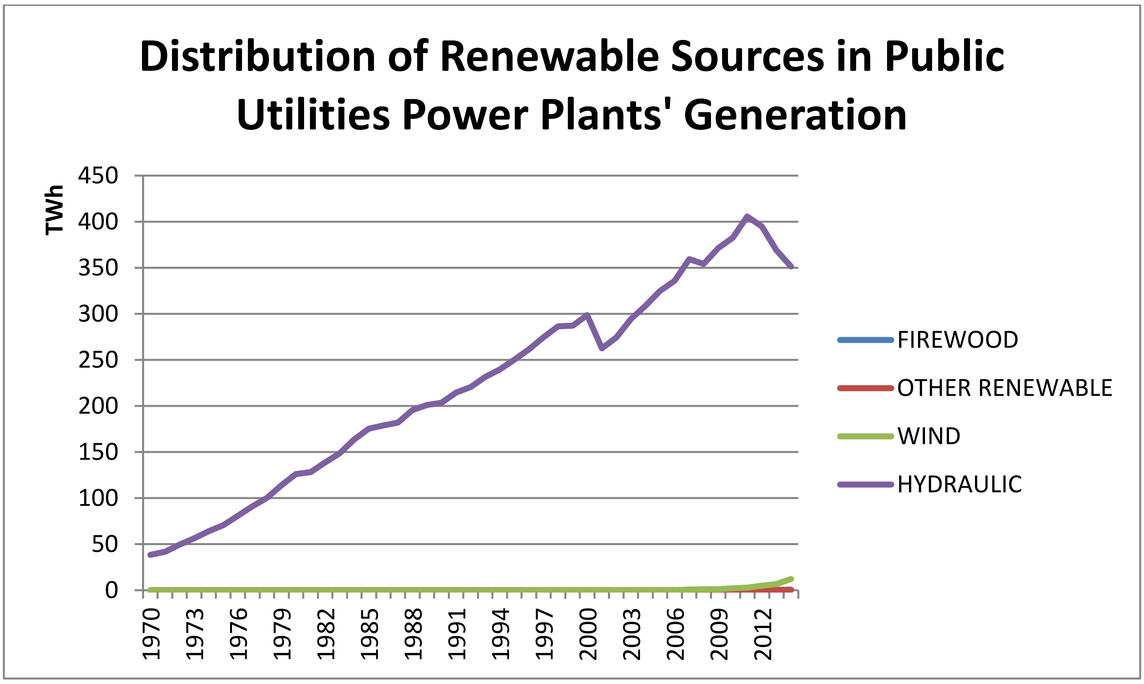


Figure 79: Generation by each renewable source in PU from 1970 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

From Figure 79 it is possible to see the importance of hydro generation for Brazil and, even with a decrease in after 2011, its participation is much bigger than any other source.

As the country counts with some SP Power Plants, they must be also analyzed in terms of input and generation.

Figure 80 represents the yearly total input used by SP power plants, from the 1970's until present days, to generate electric energy.

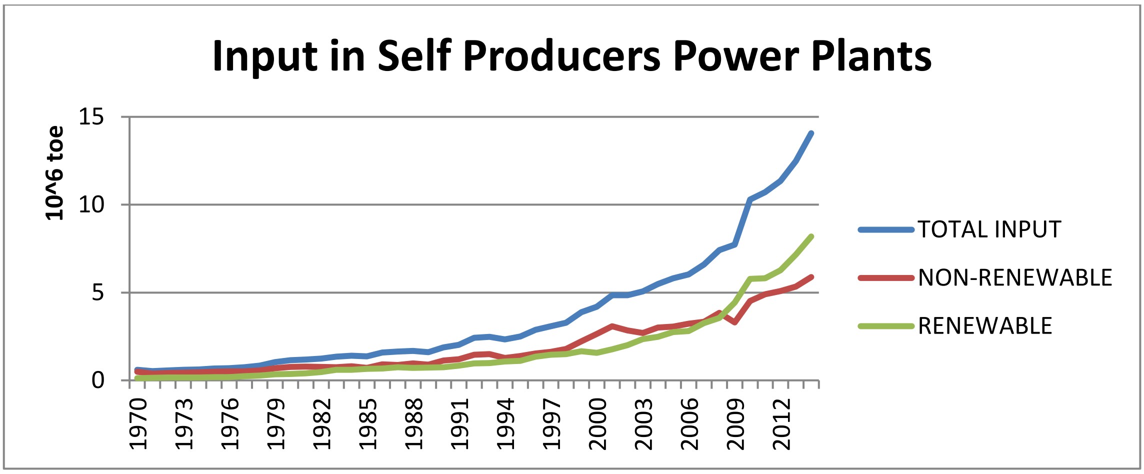


Figure 80: Input in SP power plants from 1970 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

Very different from Figure 71 Figure 80 shows that SP always have equilibrium between the use of non-renewable and renewable input with the non-renewable slightly ahead the renewable. However, that changed after 2008 and the renewable input became the most used input and the difference between them started to slowly increase.

Figure 81 represents the participation of each non-renewable source in the total non-renewable input.

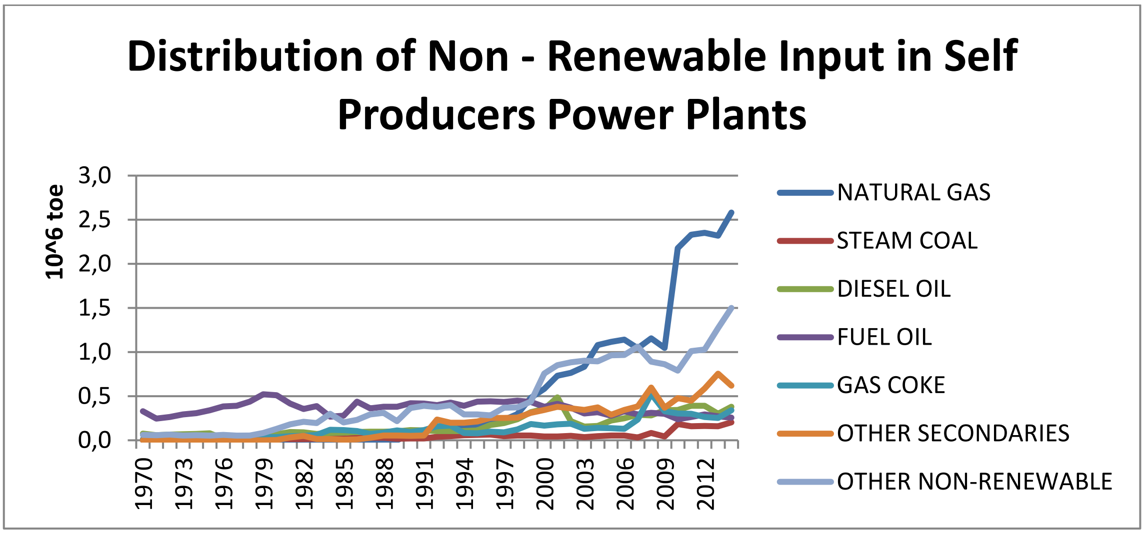


Figure 81: Non-Renewable input in SP power plants from 1974 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

As the PU, the SP also increased the use of natural gas recently, but this increase started after 2009 and not 2011 as the PU.

Figure 82 represents the participation of each renewable source in the total renewable input.

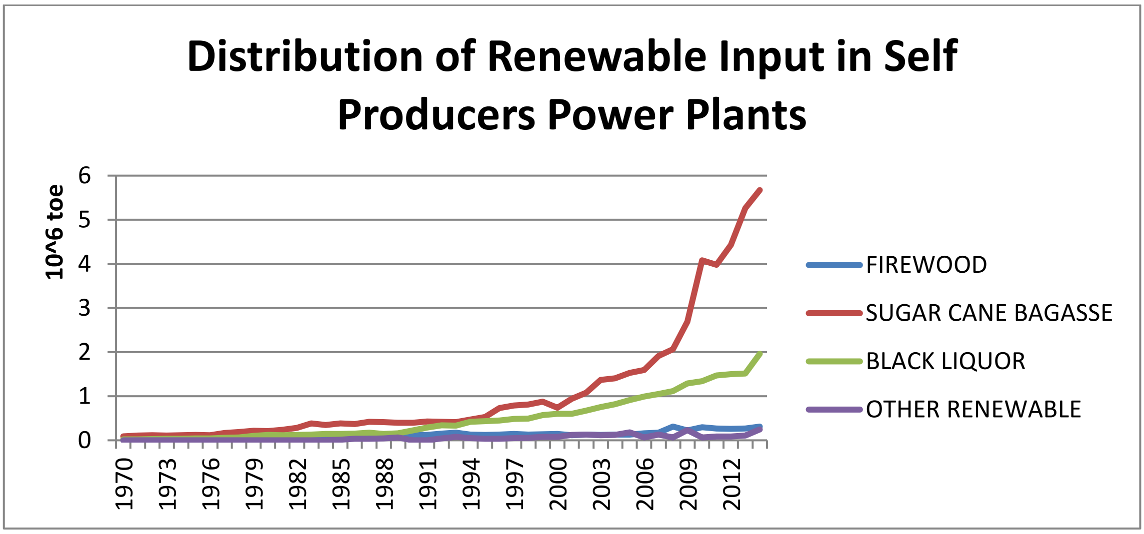


Figure 82: Renewable input in SP power plants from 1974 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

Figure 82 shows that, for the SP, the sugar cane bagasse is the most used renewable input for electricity, followed by black liquor.

Now, changing from the amount of input used to the energy generated, Figure 83 presents the total amount of electricity generated by hydro SP and thermal SP.

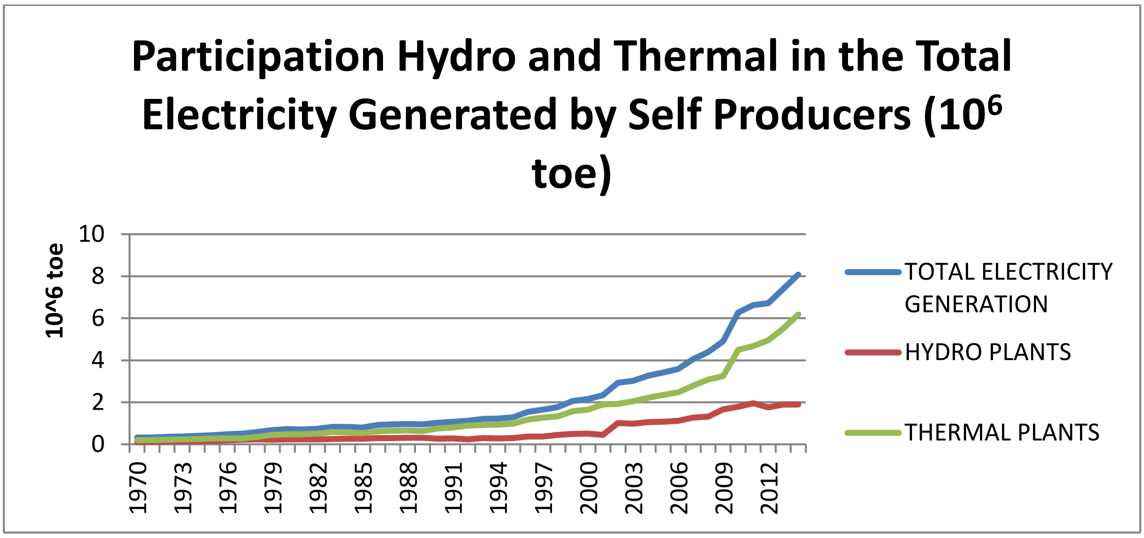


Figure 83: Participation of renewable and non-renewable in the SP total generation from 1974 until 2014 - TWh
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

Figure 83 shows the opposite of what Figure 74 presented. The SP generation is mainly thermal.

The next graphic, Figure 84, presents the total losses by the SP thermal plants.

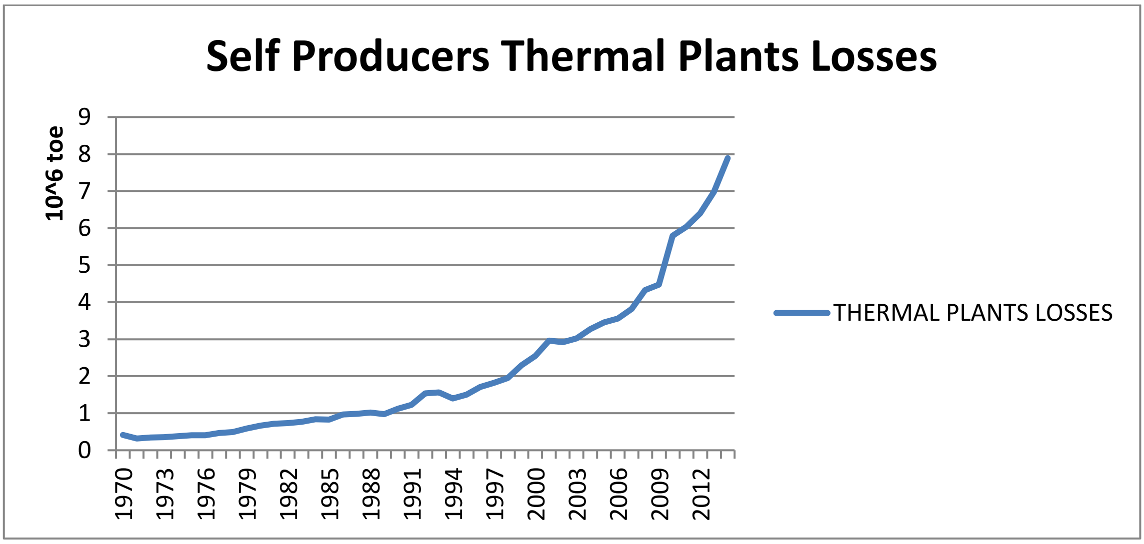


Figure 84: Losses in SP thermal plants from 1970 to 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

As happened with the PU thermal plants, the losses in the SP thermal plants are also increasing fast since 1994.

Figure 85 shows the average percentage of efficiency by year of SP thermal plants.

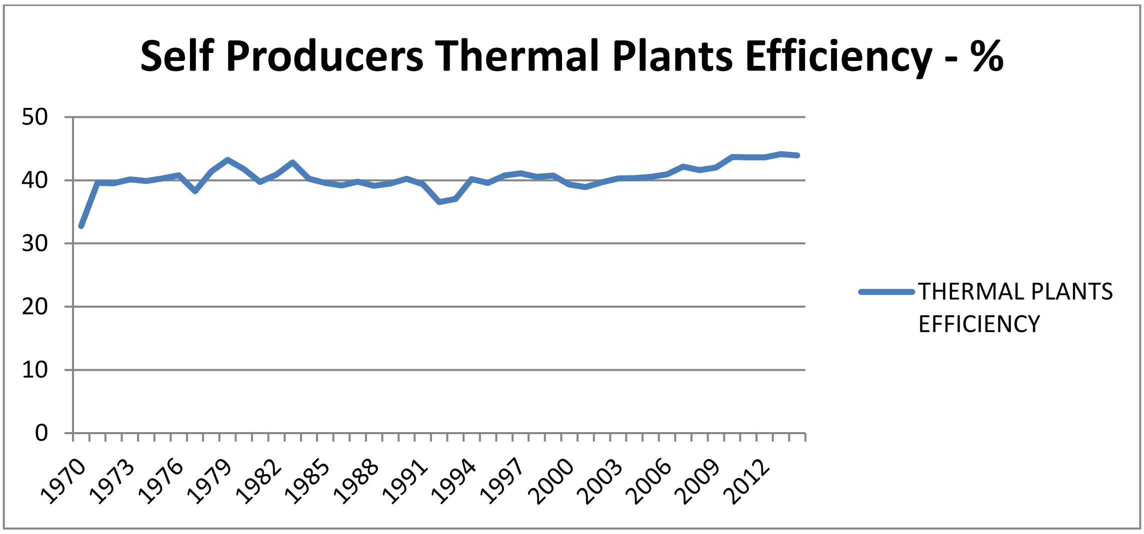


Figure 85: Percentage of the SP thermal plants efficiency from 1970 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

The efficiency of SP thermal plants has always been higher than the PU efficiency and even considering that the last one has growing fast it hasn't exceeded the efficiency presented by the SP thermal plants.

Figure 86 presents the participation of renewable and non-renewable sources in the total electricity generated yearly.

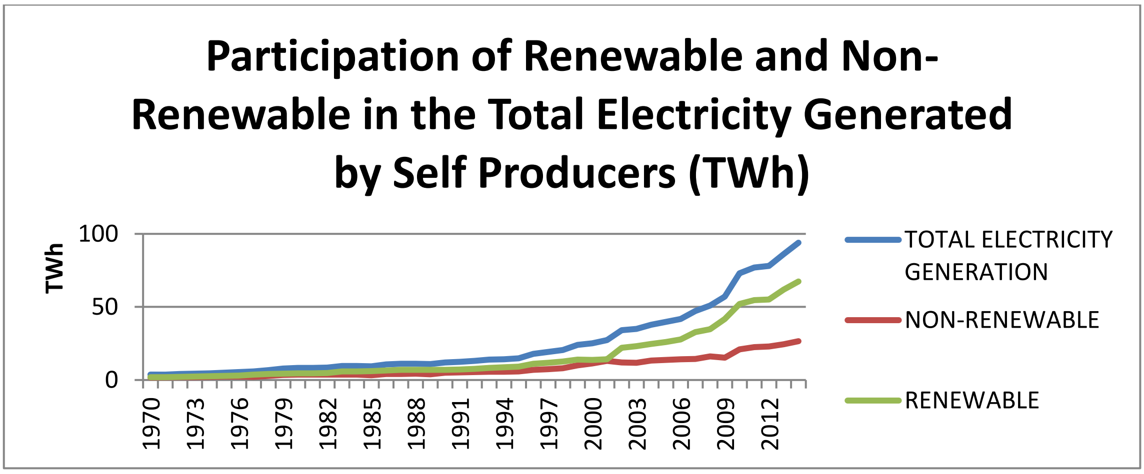


Figure 86: Participation of renewable and non-renewable in the SP total generation from 1974 until 2014 – TWh
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

In the SP case, Figure 86 shows that it is very different from the PU case where the participation of renewable and non-renewable is almost the same as the participation of thermal and hydro. In this case, even knowing that the thermal participation is much higher than the hydro, the renewable participation is much higher than the non-renewable.

This situation can be explained by analyzing Figures 87 and 88, the which present the participation of each non-renewable and each renewable source in the total non-renewable and total renewable generation, respectively.

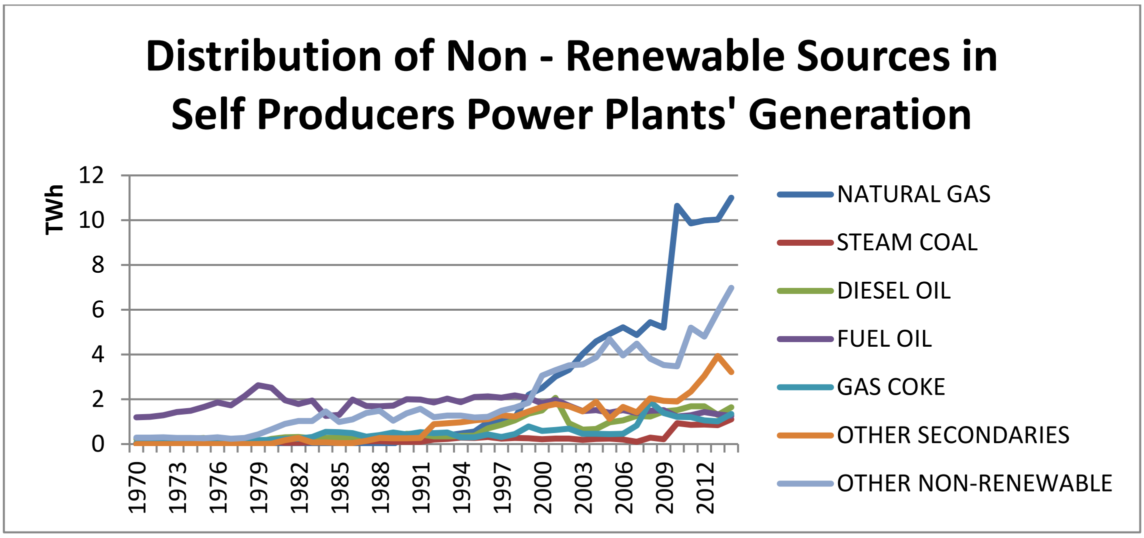


Figure 87: Generation by each non-renewable source in SP from 1970 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

Figure 87 shows, as expected, that the natural gas is the main responsible for electricity generation by non-renewable sources.

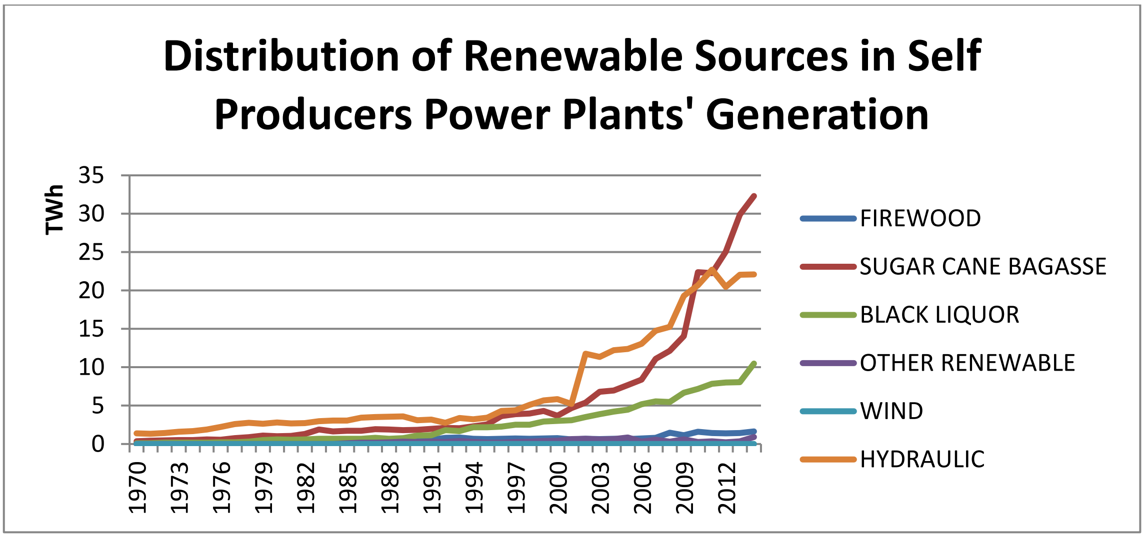


Figure 88: Generation by each renewable source in SP from 1970 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

Figure 88 shows that sugar cane bagasse is the main renewable source used to generate energy, which explain the dominance of non-renewable sources and thermal plants at the same time in the SP.

It is also interesting to notice that the hydro generation stopped growing and dropped a little bit after 2011.

Finally, the following three graphics, Figures 89, 90 and 91, represent the electric energy produced by SP and not injected in the grid.

Figure 89 shows the amount of energy generated and the amount that was not injected into the grid.

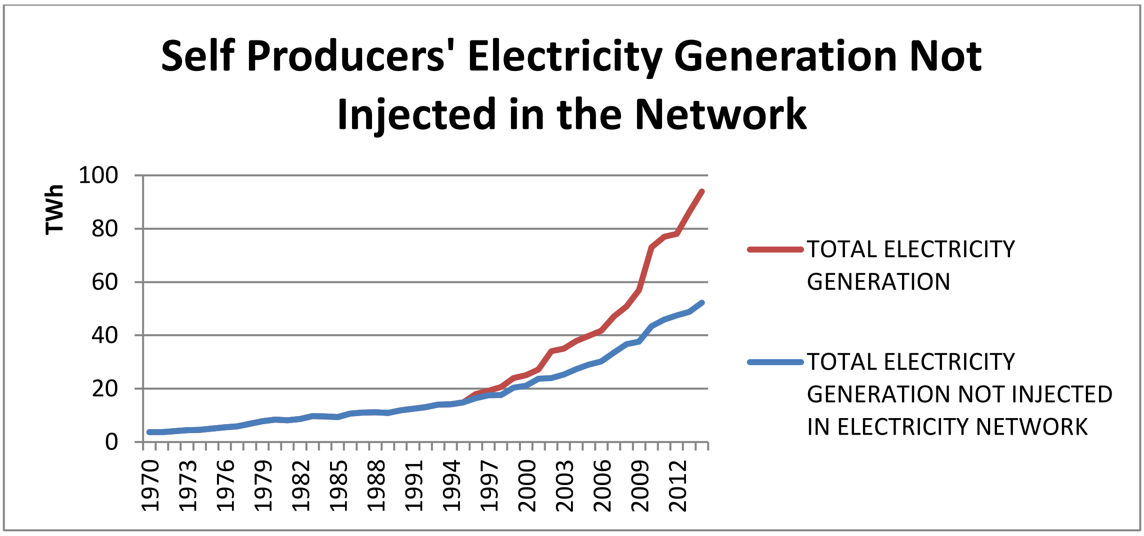


Figure 89: SP generation not injected in the grid from 1970 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

Before 1995 the energy that was generated by self-producers was, majority, not injected into the grid. However, after 1995 the amount of energy injected in the grid started to grow. That is because of the establishment of SINTREL in 1993, as was commented in the theoretical overview on the evolution of the sector.

Figure 90 show the amount of non-renewable electricity generated which was not injected into the grid.

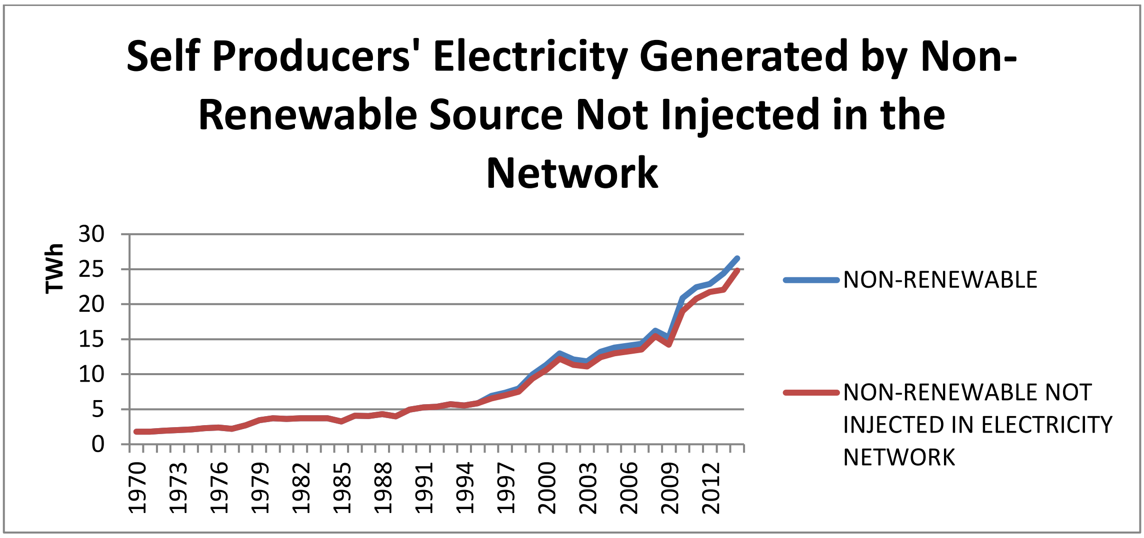


Figure 90: SP non-renewable generation not injected in the grid from 1970 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

From Figure 90 it is possible to see that almost all non-renewable energy generated wasn't injected into the grid.

Figure 91 shows the amount of renewable energy generated which was not injected into the grid.

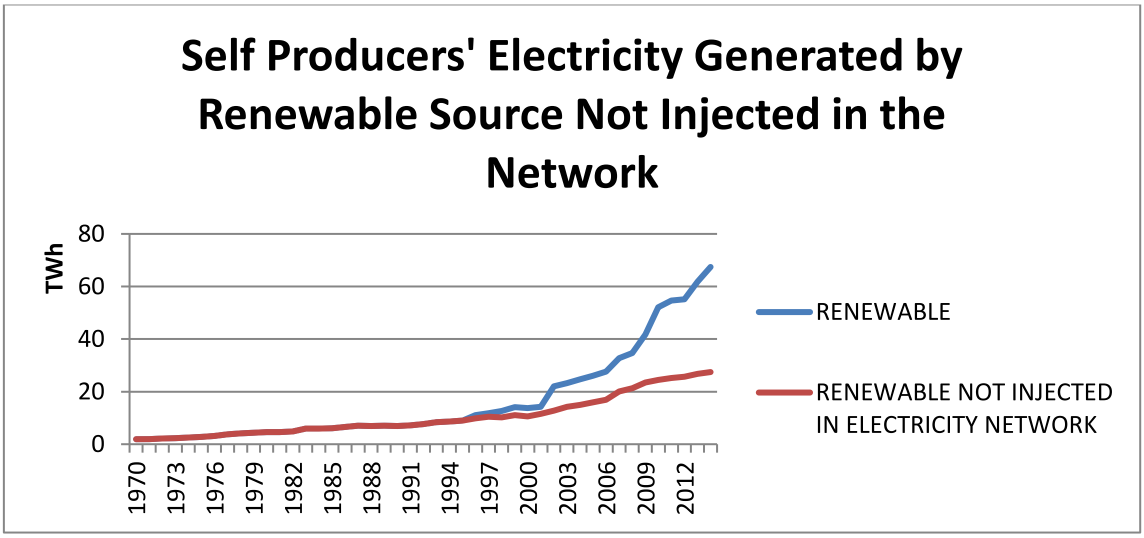


Figure 91: SP renewable generation not injected in the grid from 1970 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

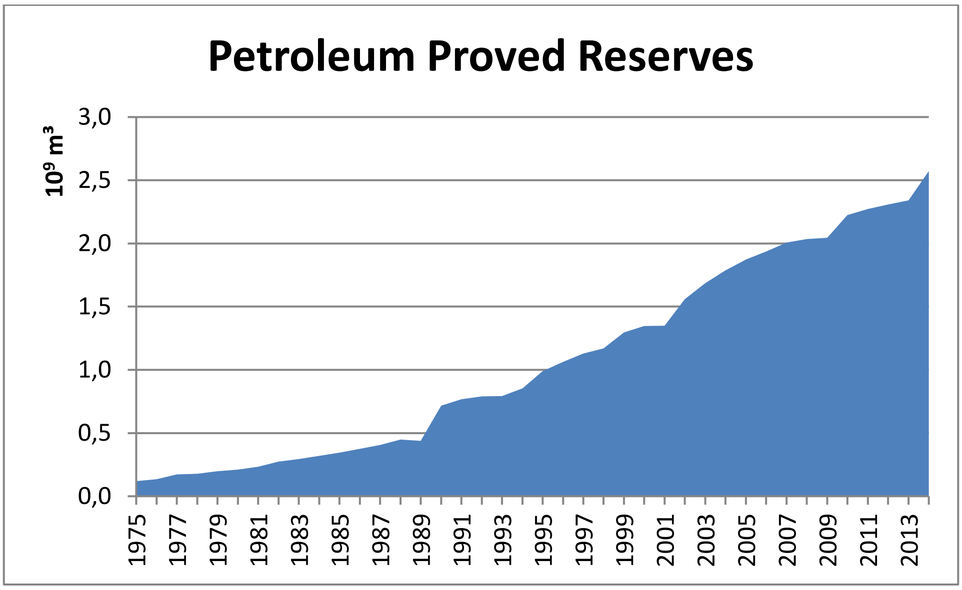
From Figure 91 it is possible to see that almost half of the renewable energy generated is injected in the grid. Probably because it is easier to sell renewable energy to the grid due to alternative energy policies.

After address the generation in the past years, the next section will present the reserves of energy sources that can be used to generate electricity.

Reserves

The reserves are presented in some cases as proved reserves and others as estimated reserve and it can be related with the interest to invest or not in a particular type of power plant.

Figure 92 presents the confirmed reserves of petroleum.



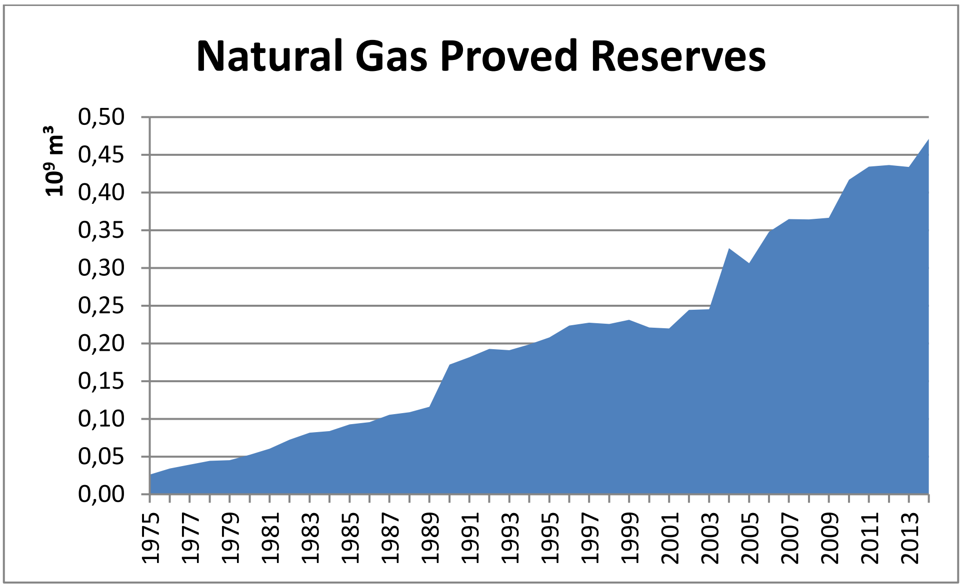
Note 1: From 1990 to 1998, criteria adopted from both SPE and WPC, which slightly increased reserves in comparison to previous years. From 1999 on values are based on ANP Decree No. 009/2000.

Note 2: Developing fields are considered.

Figure 92: Petroleum proved reserves from 1975 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

The petroleum proved reserves have been increasing.

Figure 93 presents the proved reserves of natural gas.



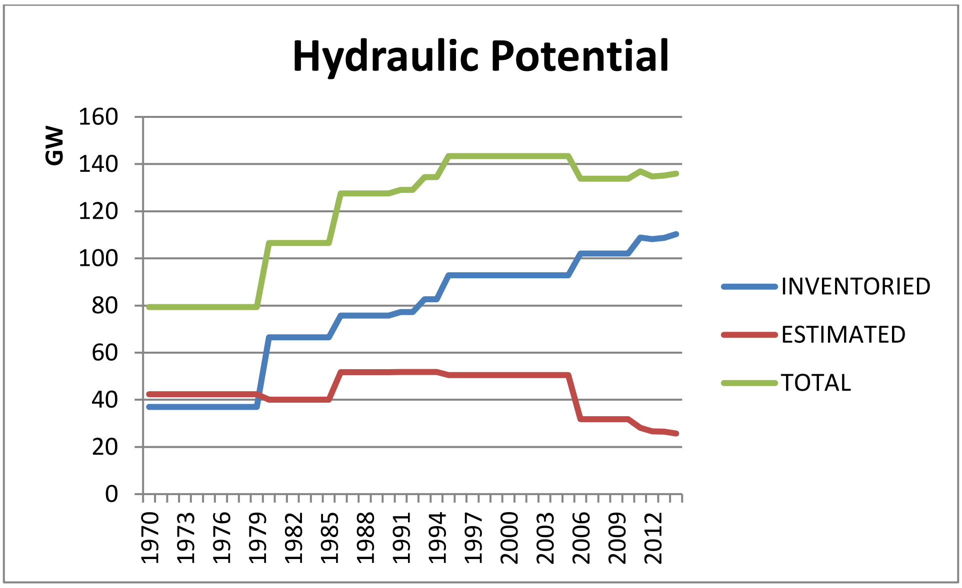
Note 1: From 1990 to 1998, criteria adopted from both SPE and WPC, which slightly increased reserves in comparison to previous years. From 1999 on values are based on ANP Decree No. 009/2000.

Note 2: Developing fields are considered.

Figure 93: Natural gas proved reserves from 1975 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

The natural gas reserves have been increasing, however, it had a slightly decrease between 2003 and 2004.

Figure 94 presents the inventoried, estimated and total hydraulic potential in the country.

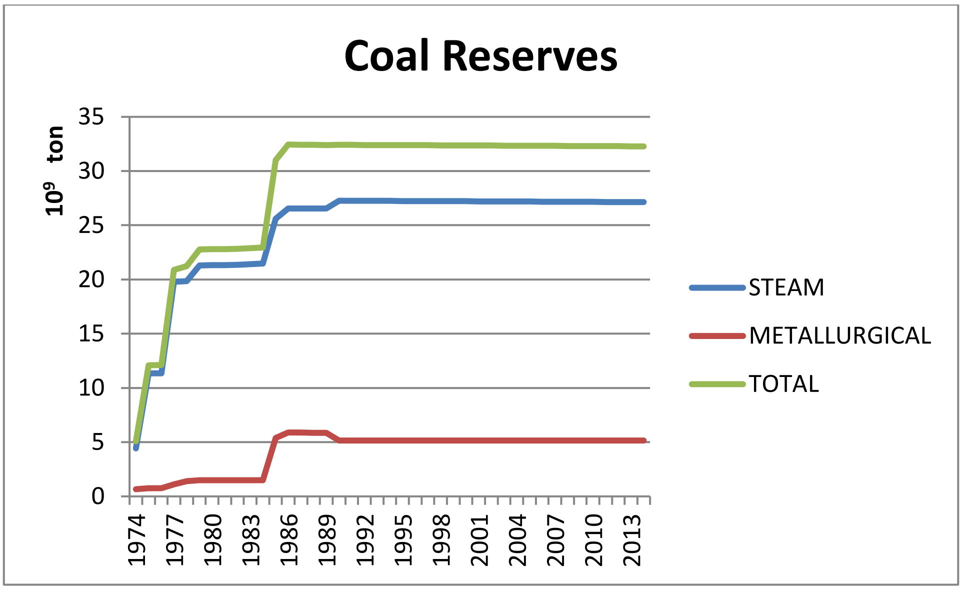


Note 1: Firm energy

Figure 94: Hydraulic inventoried, estimated and total potential from 1970 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

As the inventoried potential is growing the estimated one in decreasing, however, the decrease was bigger than the growth in the inventoried making the total potential decrease after 2004.

Figure 94 presents the reserves of coal.

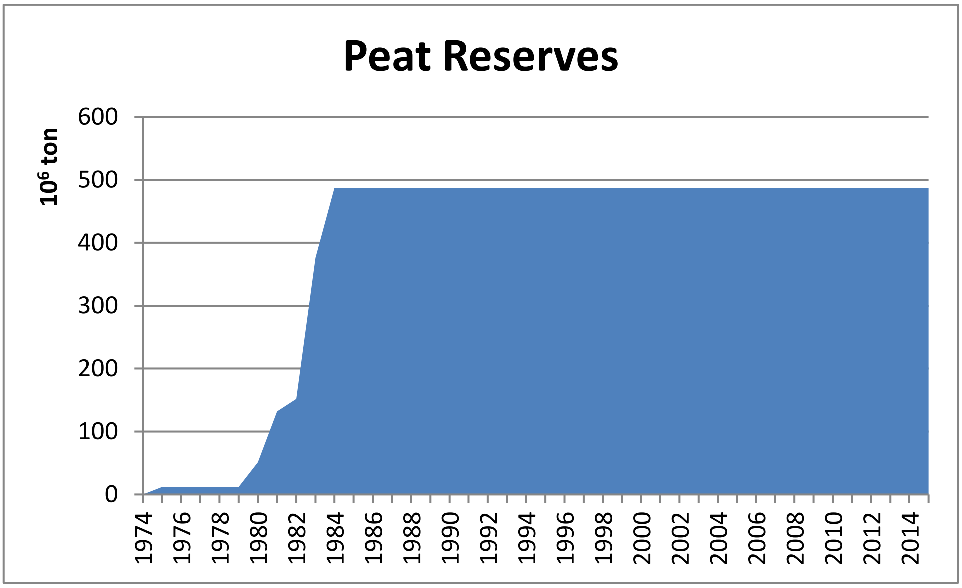


Note 1: Includes measured, indicated and inferred reserves.

Figure 95: Coal reserves from 1974 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

The steam coal and the metallurgical coal reserves are almost constant since 1990.

Figure 96 presents the reserves of peat.

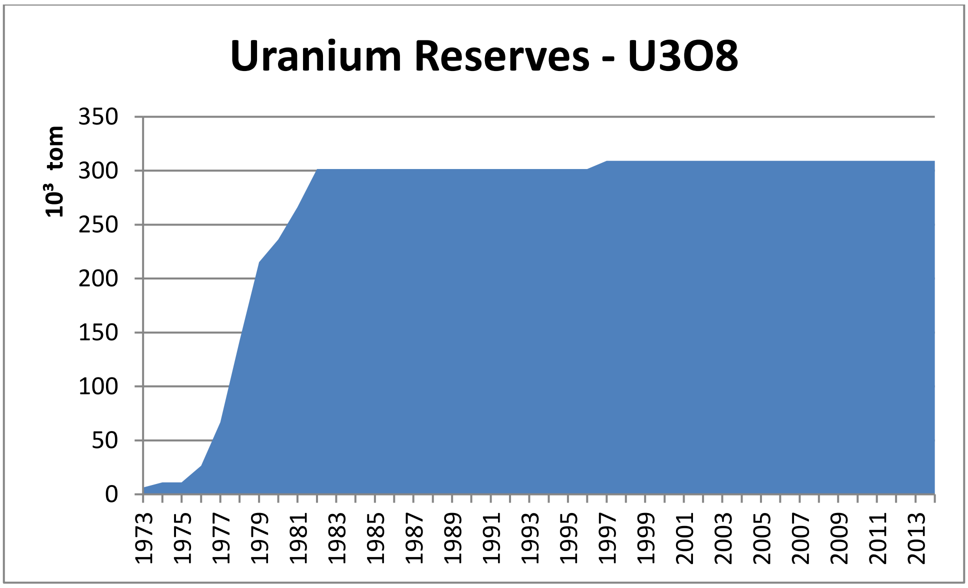


Note 1: Includes measured, indicated and inferred reserves.

Figure 96: Peat reserves from 1974 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

Since 1984 the reserves of peat are constant.

Finally, Figure 97 presents the reserves of uranium U_3O_8.



Note 1: Includes measured, indicated and inferred reserves

Figure 97: Uranium reserves from 1973 until 2014
Source: Balanço Energético Nacional, EPE, Ministério de Minas e Energia, 2015

From Figure 97 it is possible to see that the reserves of uranium are almost constant with a slightly increase between 1996 and 1997.

This topic aimed to analyze the evolution of Brazilian power industry by theoretical review and preliminary data analysis, which can be seen as complementary.

Besides, the data analysis also pointed that the hydro source is the main source of energy used to generate electricity in the country with the bigger participation in both, installed capacity and generation. However, its generation has been decreasing in the last years: increasing the use of thermal plants, the amount of CO_2 emission, the electricity costs and decreasing the security of the supply.

The analysis also pointed to an increase in thermal installed capacity and generation since 2001 as a consequence of the last electricity crisis; and also, an increase in wind and solar (especially wind), as the country has a goal of reducing GHG emissions until 2020.

Furthermore, this topic also made possible to realize the difference between the electric mix between SP and PU, being both very different in what concerns the installed capacity and the generation, but one should keep in mind that the PU has a much higher participation than SP in the total installed capacity and total generation.

GHG in Brazil

GHG or greenhouse gas, according to IPCC (2014),

> "are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself, and clouds. This property causes the greenhouse effect. Water vapour (H2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere".

In what concerns Brazil, even being a Non-Annex I country, which mean that Brazil has no binding commitments to the Framework Convention on Climate Change, the country established the National Policy on Climate Change (PNMC), from the Law 12.187/2009 (D.O.U. DE 29/12/2009, P. 109 extra edition), which sets the voluntary national commitment to adopt mitigation actions in order to reduce their emissions of GHG for something between 36.1% and 38.9% compared to projected emissions until 2020. According to the Decree 7.390/2010 about the PNMC (D.O.U. DE 10/12/2010, P. 4), which regulates the National Policy on Climate Change, the projection of greenhouse gas emissions for 2020 was estimated at 3,236 Gt CO_2e. Thus, the corresponding reduction in the percentage established is between 1,168 Gt CO_2e and 1,259 Gt CO_2e, respectively.

Figures 98, 99 and 100 give a portrayal of the emissions, removal and bunker in Brazil related with the following gases: Carbone Dioxide (CO_2), Carbon Monoxide (CO), Methane (CH_4), Nitrous Oxide (N_2O), Non-Methane Volatile Organic Compound (NMVOC), Nitric Oxide and Nitrogen Dioxide (NO_x), Hydrofluorocarbons (they are substitutes of the Chlorofluorocarbons HFC – 23, HFC – 125, HFC – 134a, HFC – 143a, HFC – 152a), Perfluorocarbons (CF_4 and C_2F_6) and Sulphur Hexafluoride (SF_6). The values presented in figures are expressed in CO_2e t GWP (Tons of Carbone Dioxide Equivalent Global Warming Potential).

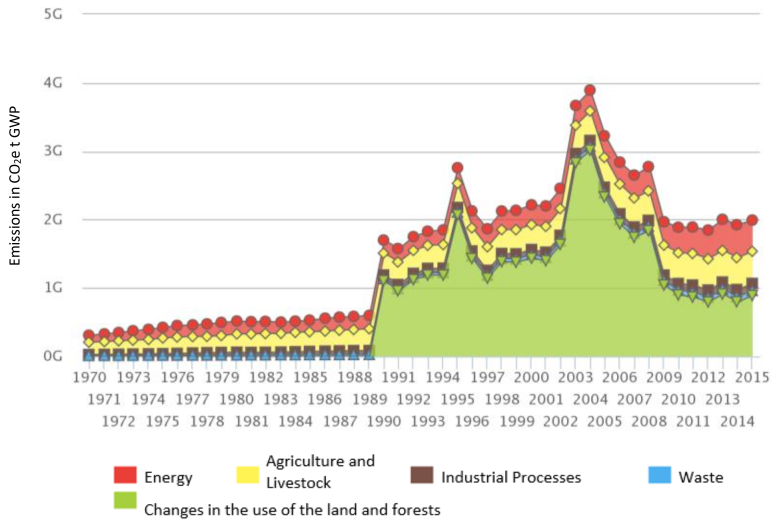


Figure 98: Total CO_2e emissions from 1970 until 2015 in t (GWP)
Source: SEEG 2015

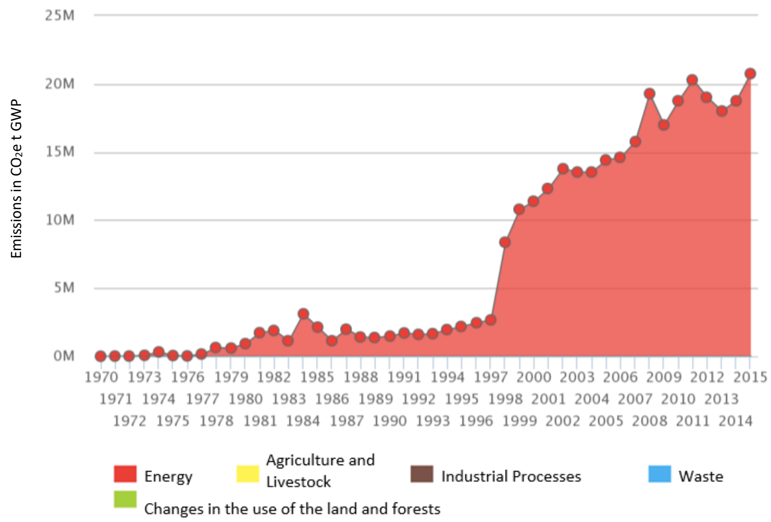


Figure 99: Total bunker CO_2e emissions from 1970 until 2015 in t (GWP)
Source: SEEG 2015

Bunker corresponds to international maritime and air transport emissions and only contributes for energy emissions. As a rule, it should be reported separately as they refer to emissions with responsibility for more than one country.

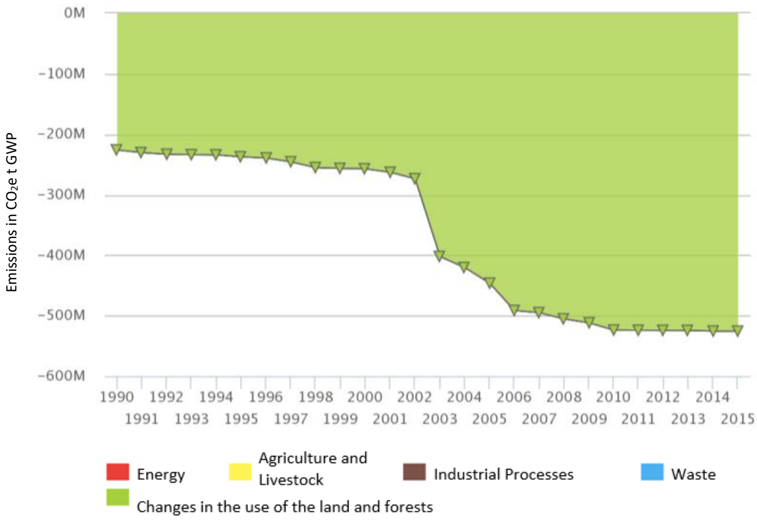


Figure 100: Total CO_2e removal from 1970 until 2015 in t (GWP)
Source: SEEG 2015

Removal is done by calculating the amount of carbon gases fixed by vegetation growth in areas of forests, regeneration of pastures, natural preservation and indigenous territory, so, the removal only appears in the data as land use change.

From Figures 98 to 100 it is possible to conclude that when emissions from land use change are decreasing dramatically, the energy and agriculture and livestock emissions have been increasing in the last years. It is important to remind that land use change also consider indirect emissions from the energy and agriculture and livestock sectors as, the construction of power plants (especially the new projects in Amazon), land for biofuels and deforestation to expand land for grazing and food production are evaluated as land use change.

For better understand the GHG emissions in the last years see SEEG (n.d.).

Appendix C: Evolution of the main reservoirs level

The reservoirs are separated by river – each graphic correspond to one specific river.

The values represent the percentage of the reservoir that is full. Besides, it is important to consider when analyzing figures that, according to Lorenzo (2002), the ideal level is 90%. Another important aspect to consider is that the level of the reservoir does not correspond to the level of precipitation in the same period as the reservoir works as a buffer to the system, though, the reservoirs usually presents a characteristic seasonal/cyclic variation.

It is also interesting to remember that the regularization capacity of the reservoirs is 5 months and it is expected to drop to 4 months until 2021.

Figures 101 to 110 represents the level of the reservoirs in the power sector, as presented by ONS, and can be noticed that the levels are, in many cases, dropping down and in some cases, are already empty.

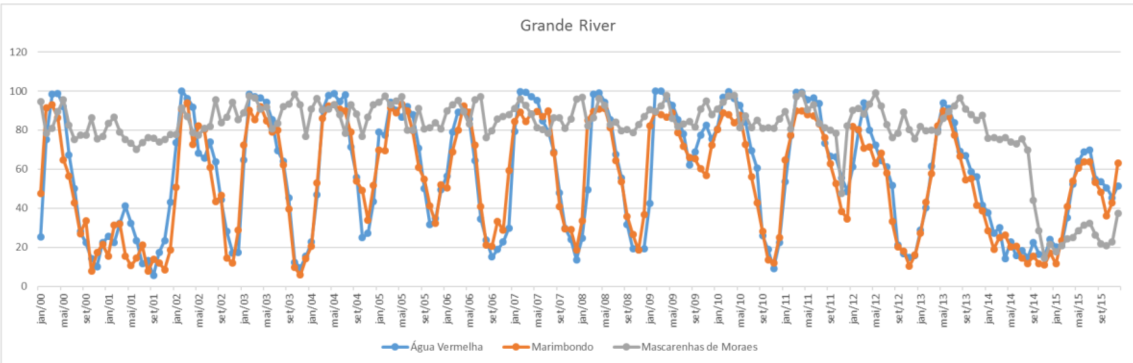


Figure 101: Grande river reservoir levels
Operador Nacional do Sistema Elétrico 2015

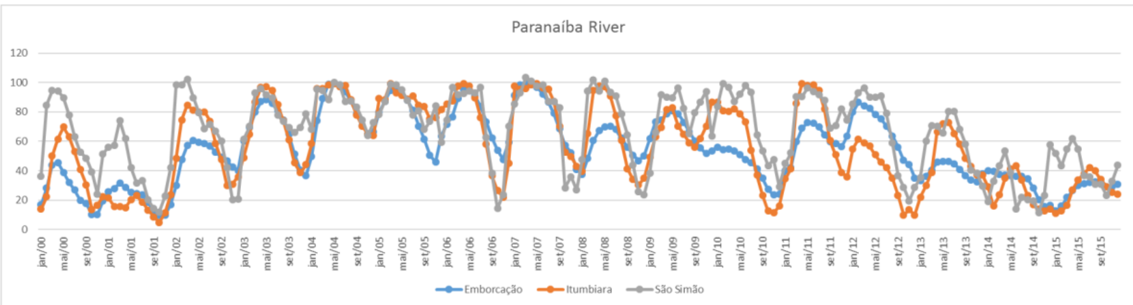


Figure 102: Paraíba river reservoir levels
Operador Nacional do Sistema Elétrico 2015

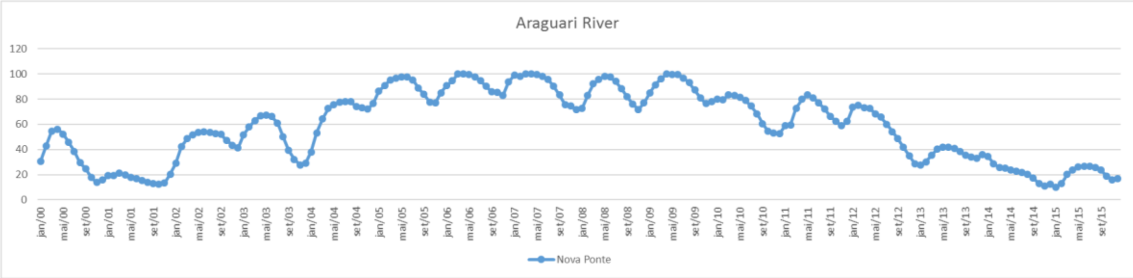


Figure 103: Araguari river reservoir levels
Operador Nacional do Sistema Elétrico 2015

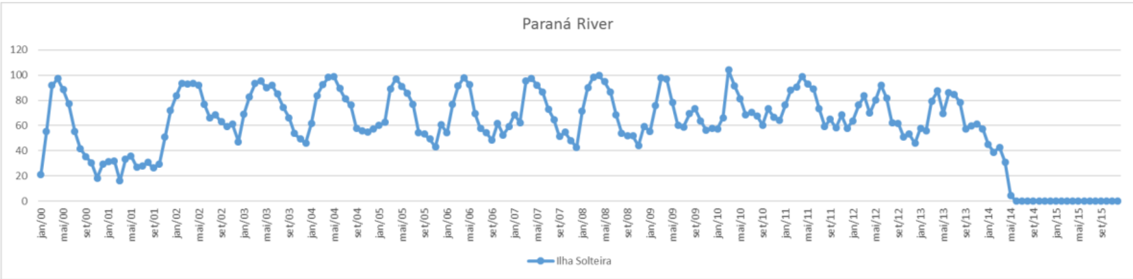


Figure 104: Paraná river reservoir levels
Operador Nacional do Sistema Elétrico 2015

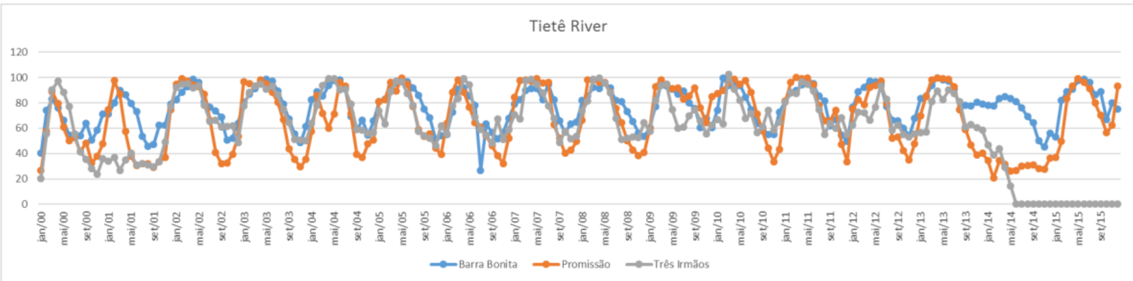


Figure 105: Tietê river reservoir levels
Operador Nacional do Sistema Elétrico 2015

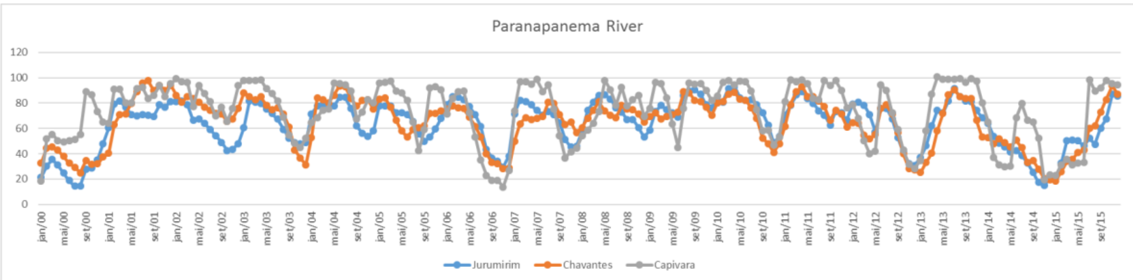


Figure 106: Paranapanema river reservoir levels
Operador Nacional do Sistema Elétrico 2015

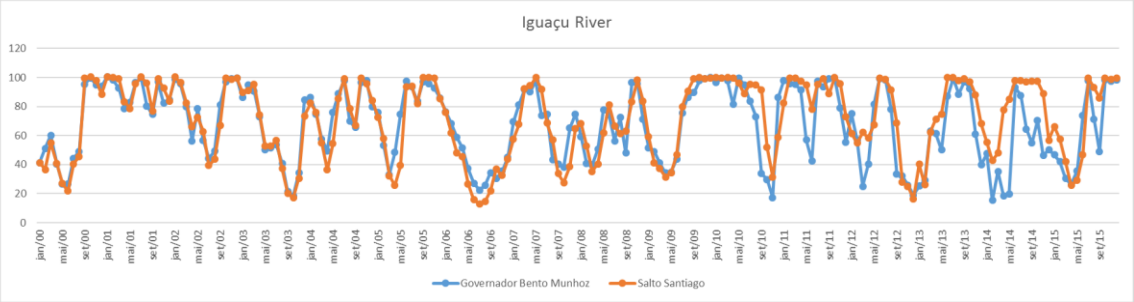


Figure 107: Iguaçu river reservoir levels
Operador Nacional do Sistema Elétrico 2015

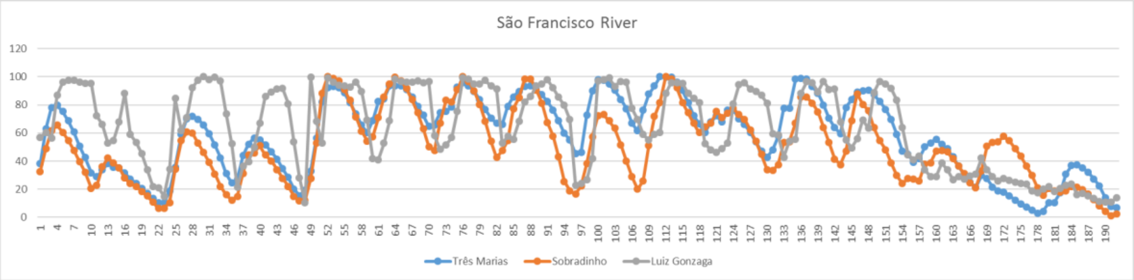


Figure 108: São Francisco river reservoir levels
Operador Nacional do Sistema Elétrico 2015

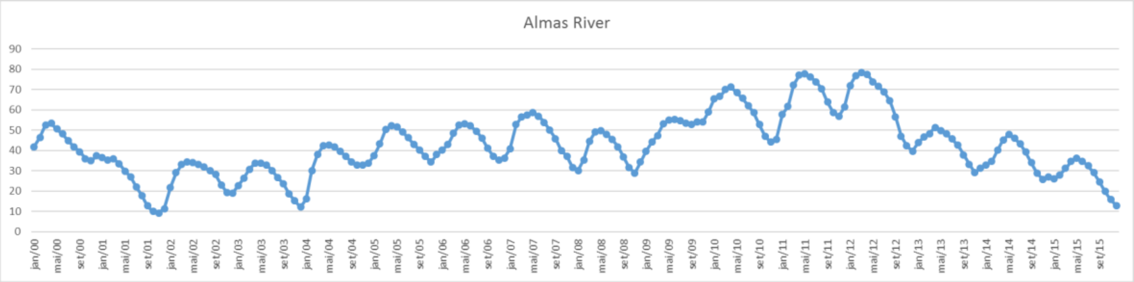


Figure 109: Almas river reservoir levels
Operador Nacional do Sistema Elétrico 2015

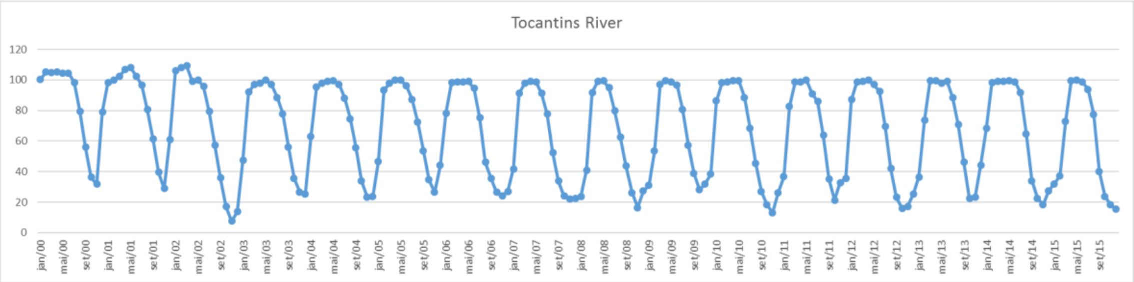


Figure 110: Tocantins river reservoir levels
Operador Nacional do Sistema Elétrico 2015

Appendix D: Smart Grids Pilot Projects

Table 20: Areas researched by each utility

Utility	Smart Meter	Distribution Automation	Distributed Generation	Storage Systems	Electric Vehicles	Telecomm	IT	Smart buildings	New services	Others	Demonstrative projects	Inova Energy
CEMIG – D	■	■	■	■	■	■	■		■	■	■	N
CELESC – DIS	■	■	■				■	■				S
AES ELETROPAULO	■	■	■		■	■	■	■	■	■	■	N
AMPLA	■	■	■	■	■	■	■	■	■	■	■	S
LIGHT	■	■	■	■	■	■	■	■	■		■	S
COELCE	■	■				■	■				■	N
COELBA	■	■	■			■	■			■		N
ELEKTRO	■	■	■		■				■	■	■	S
BANDEIRANTE	■	■	■		■	■	■			■	■	S
CPFL-PAULISTA	■	■	■		■	■	■	■	■	■	■	S
CEEE-D		■	■	■		■		■				S
AES-SUL		■	■			■	■					S
CEB-DIS			■				■	■				N
CELPA	■		■									N
CELPE	■	■	■	■	■	■	■			■	■	N
EMG		■					■			■		N
ESCELSA		■							■	■	■	S
CEAL	■						■					N
CEMAR		■	■				■					N
COPEL-DIS	■	■	■	■	■	■	■	■			■	N
MANAUS ENERGIA	■	■	■			■	■			■	■	N
CELG-D			■							■		N
CERON	■						■					N
CEPISA	■											N
COSERN						■						N
DEMEI						■						S
DMEPC						■						N
ELEJOR			■									N
ELETROACRE			■									N
ELETROCAR		■										N
ENERSUL	■											N
SULGIPE							■					N

Source: Pelegrini & Vale, 2014

Appendix E: Power Sector Expansion Projections

There are many short time (10 years) energy expansion plans (for every year between 2015 and 2024 with exception of 2018) besides the medium/long time (25 years) energy expansion plan (for 2030) in Brazil. For each plan was made a series of projections considering the evolution of social, economic, and technical data and the projections can be seen in Figures 111 to 126. The data presented in Figures come from PDE (ten-year expansion plan) 2015, PDE 2016, PDE 2017, PDE 2019, PDE 2020, PDE 2021, PDE 2022, PDE2023, PDE2024 and PNE 2030.

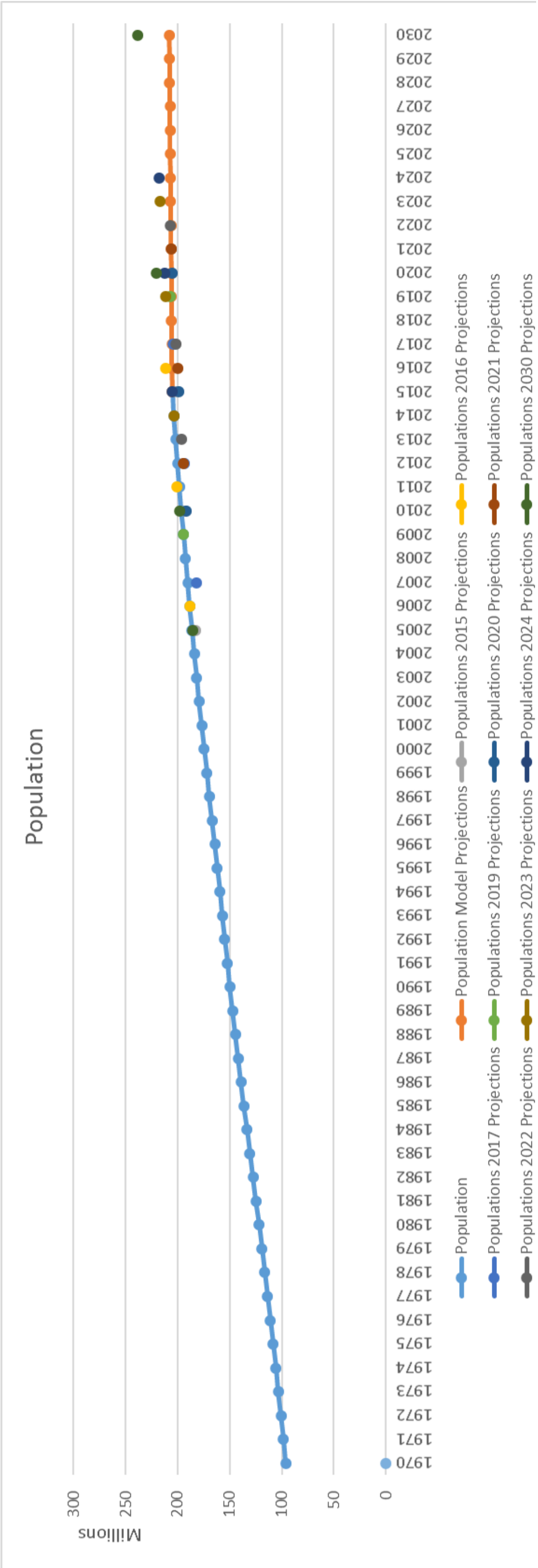


Figure 111: Projections for population growth

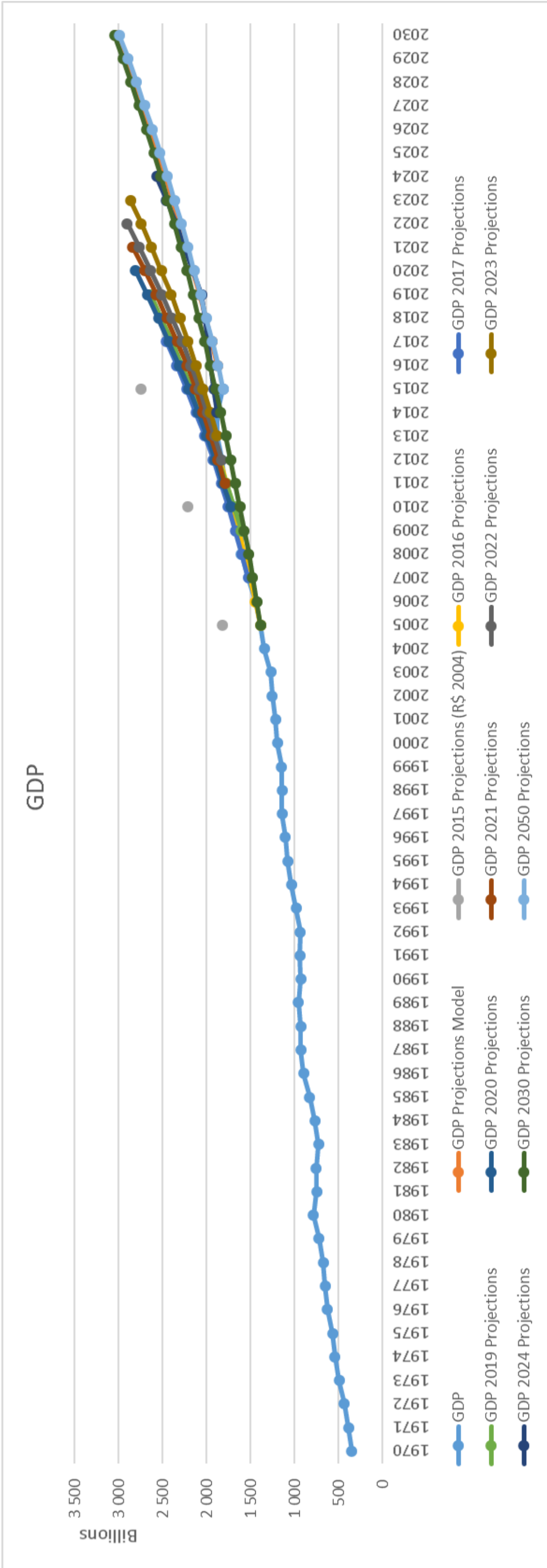


Figure 112: Projections for GDP growth

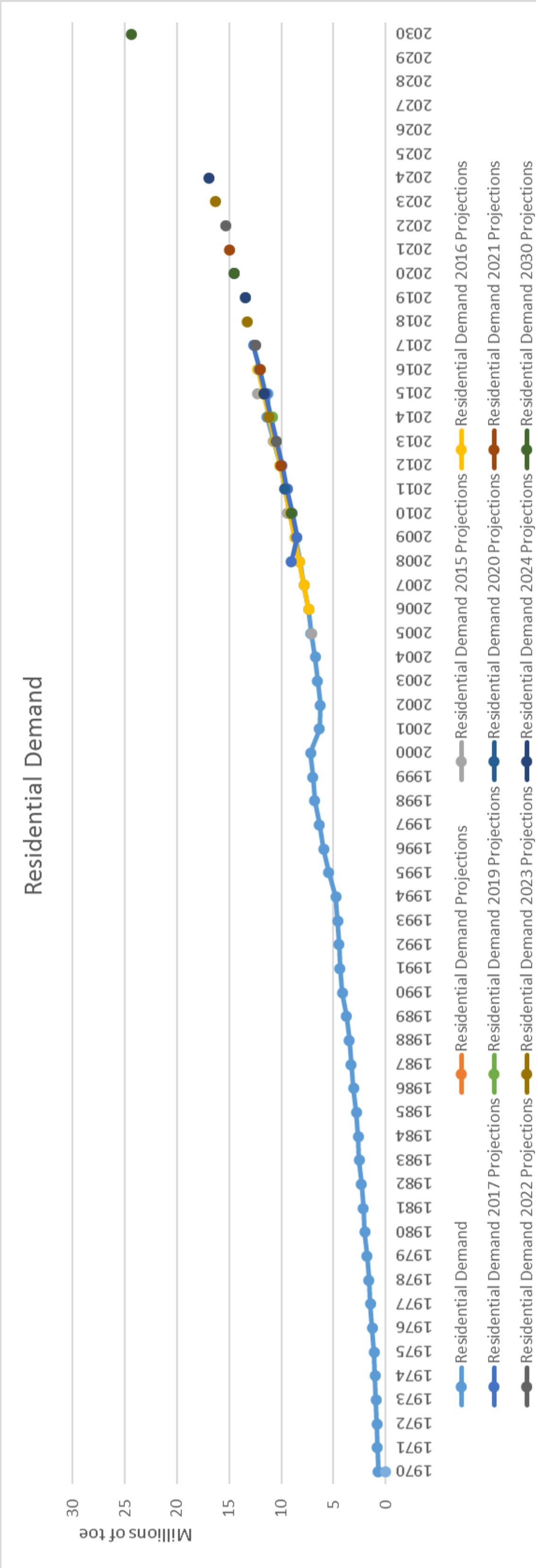


Figure 113: Projections for Residential Demand

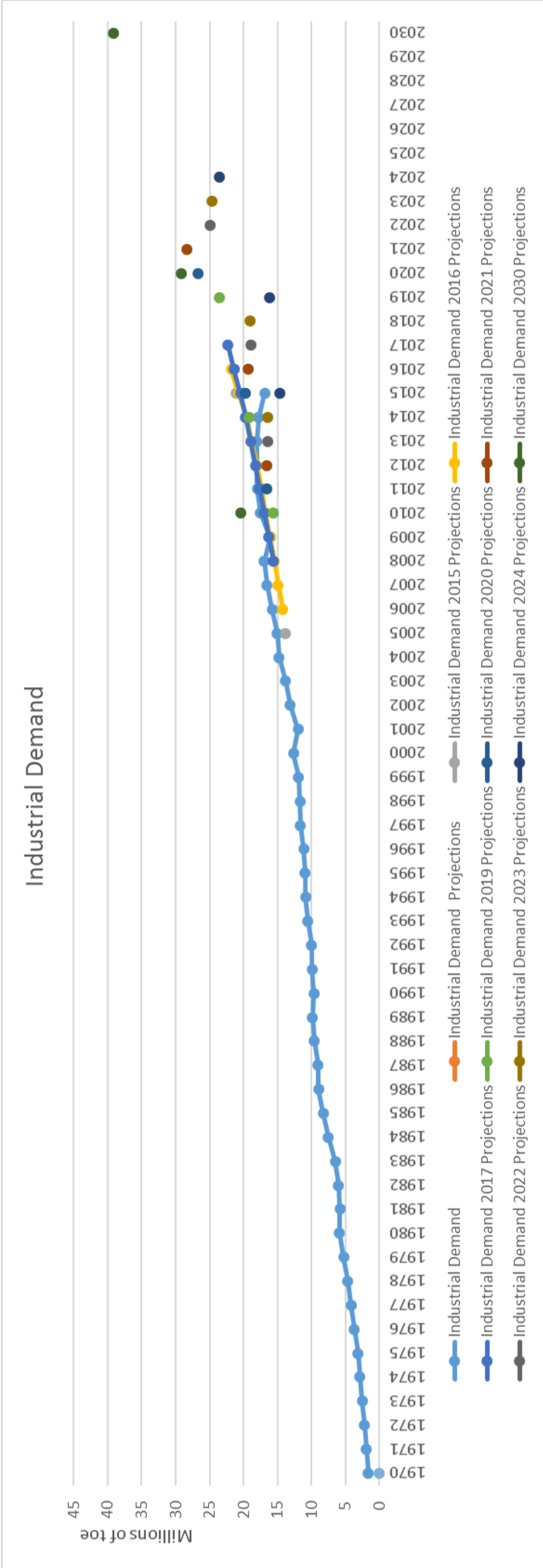


Figure 114: Projections for Industrial Demand

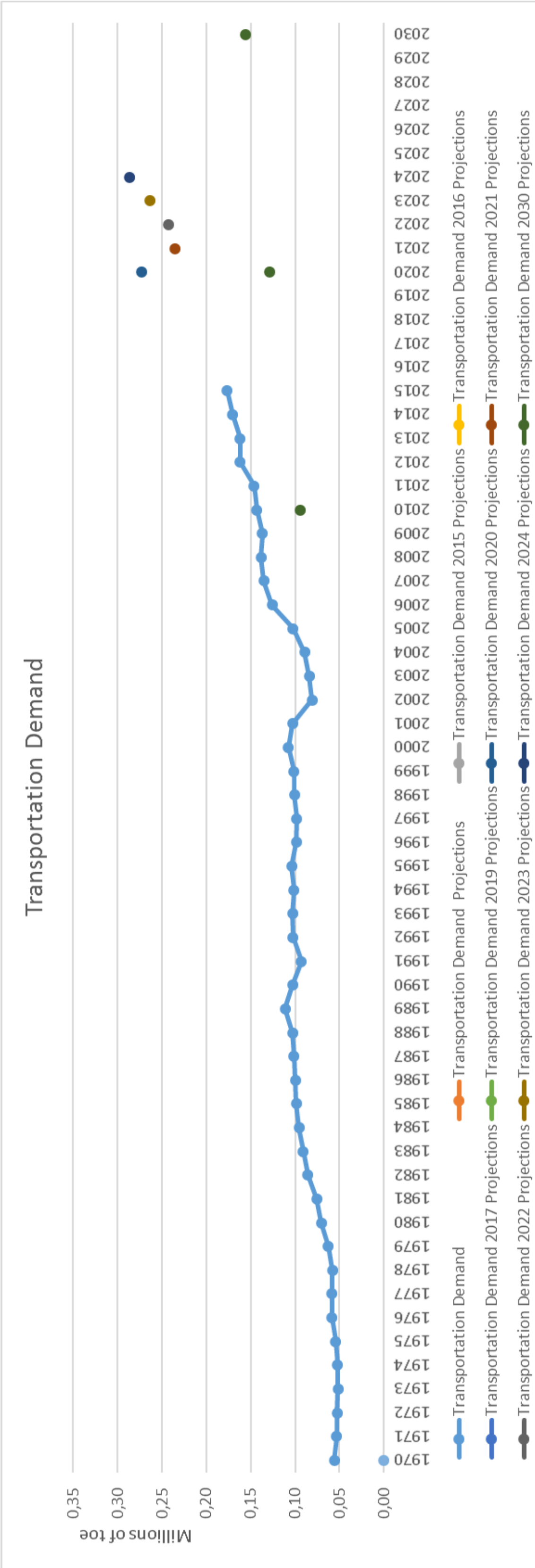


Figure 115: Projections for Transportation Demand

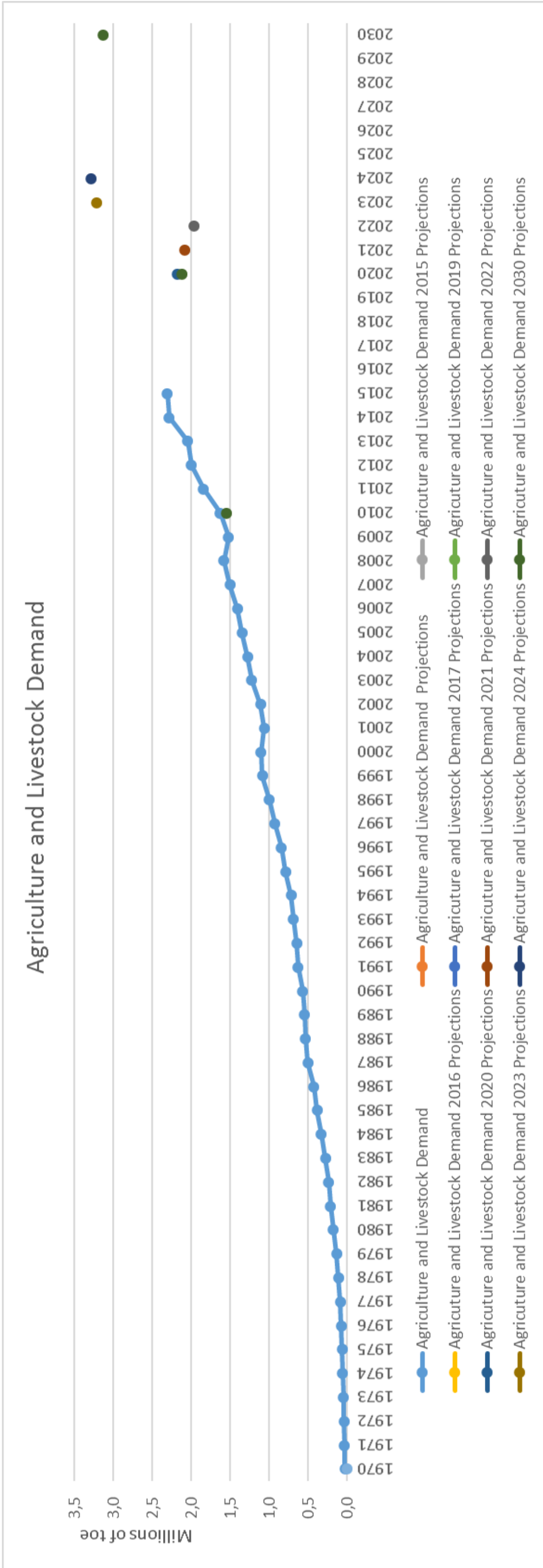


Figure 116: Projections for Agriculture and Livestock Demand

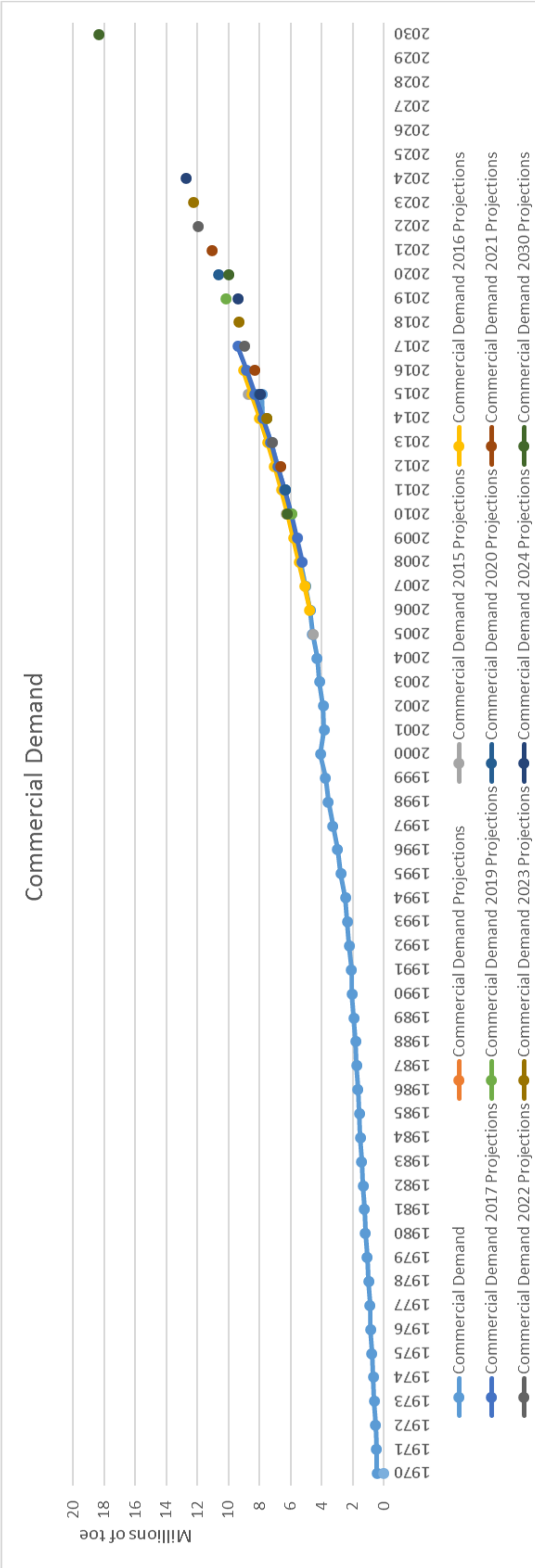


Figure 117: Projections for Commercial Demand

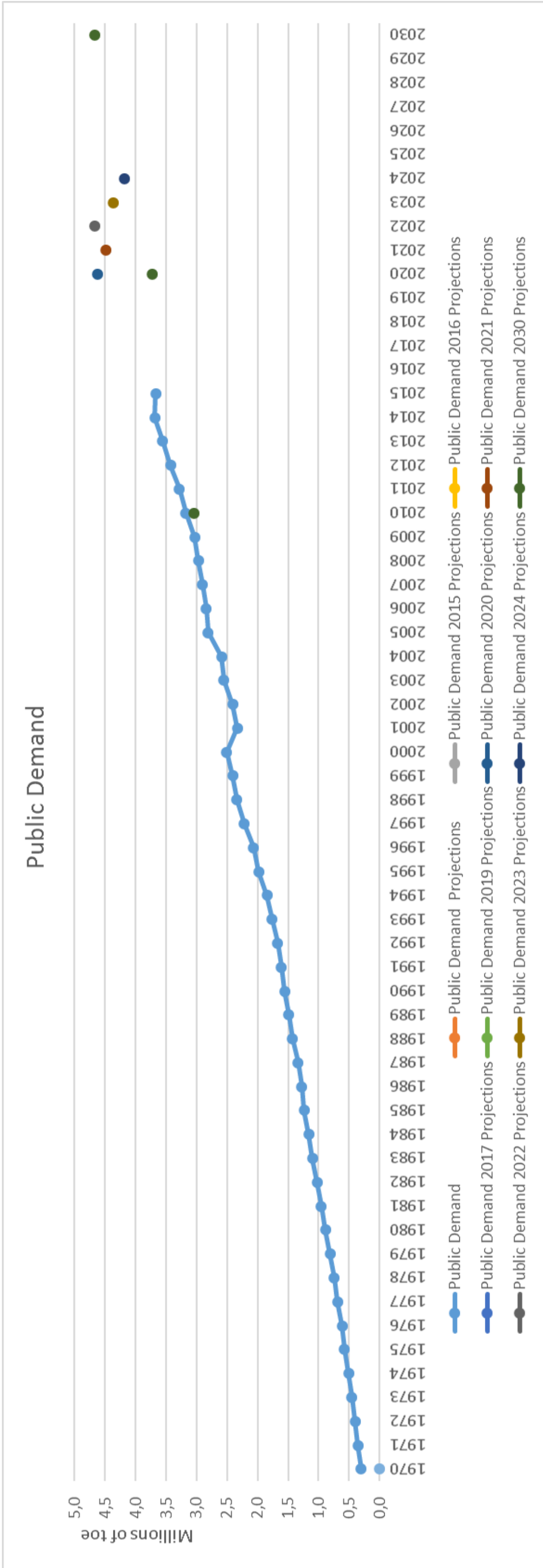
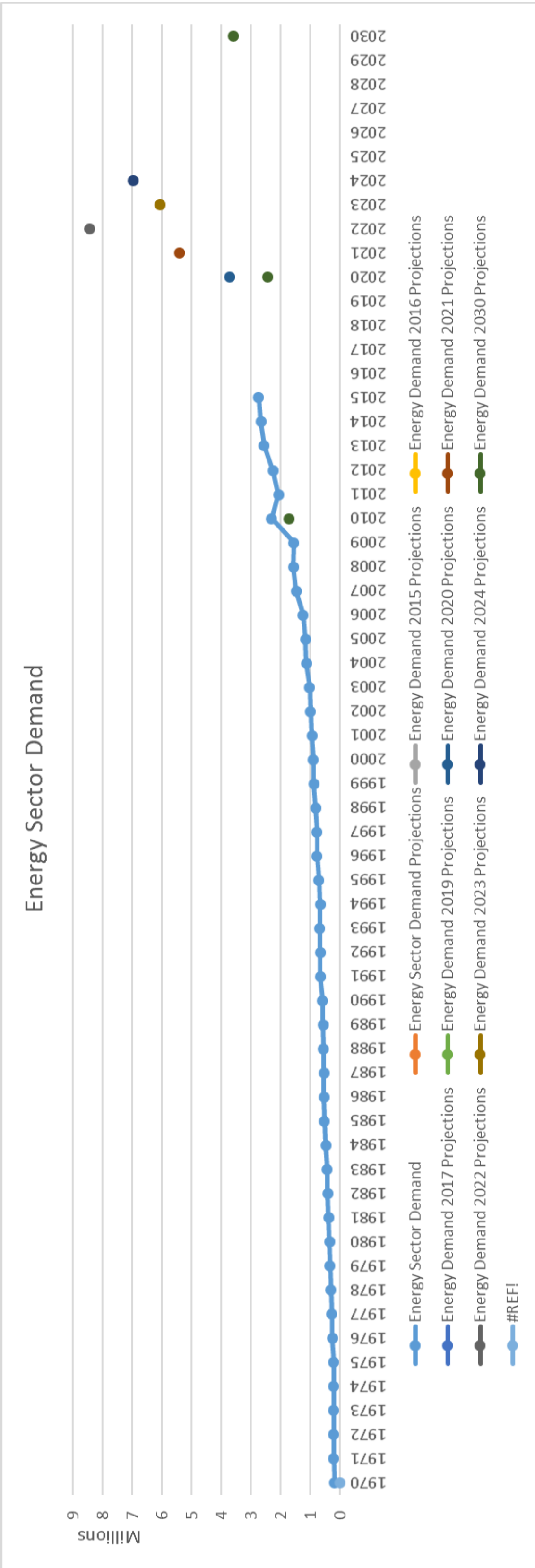


Figure 118: Projections for Public Demand



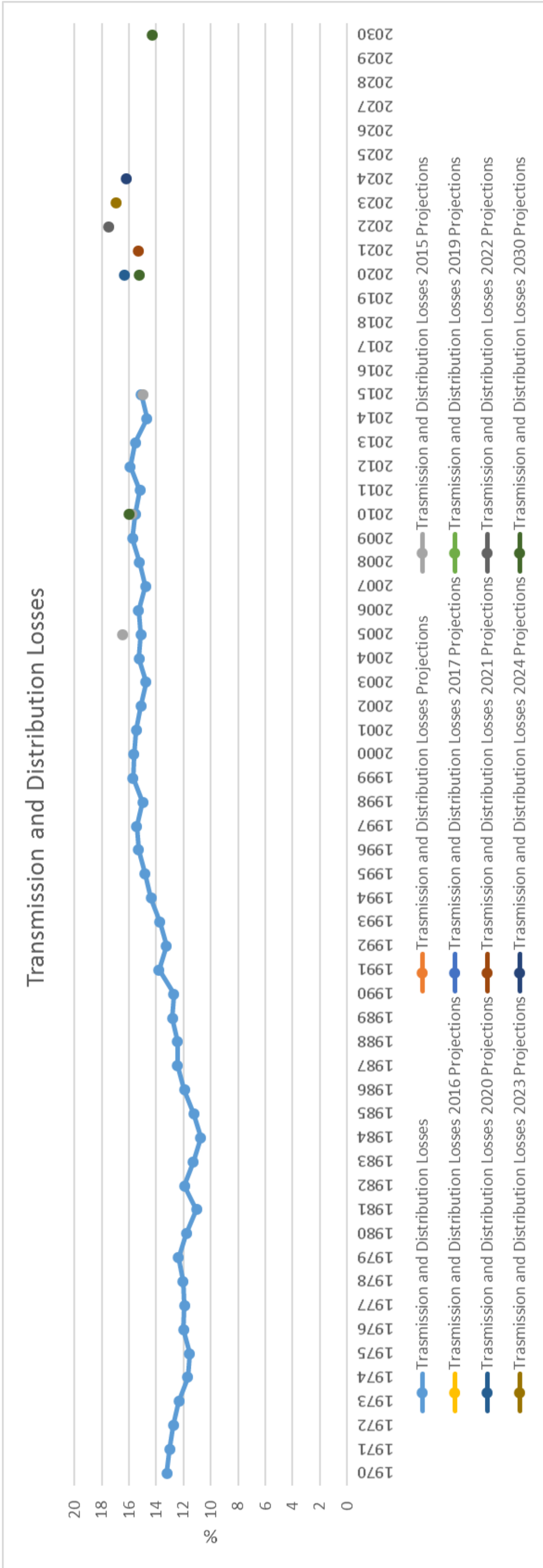


Figure 119: Projections for Energy Sector Demand

Figure 120: Projections for Transmission and Distribution Losses

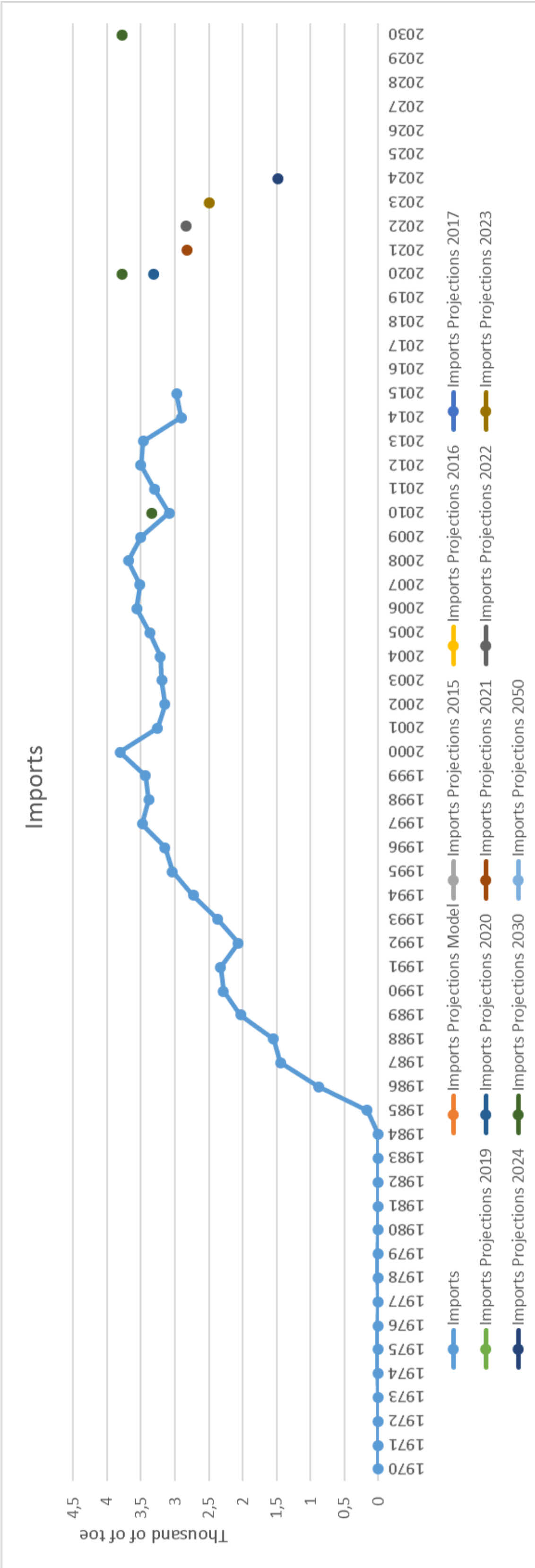


Figure 121: Projections for Electricity Imports

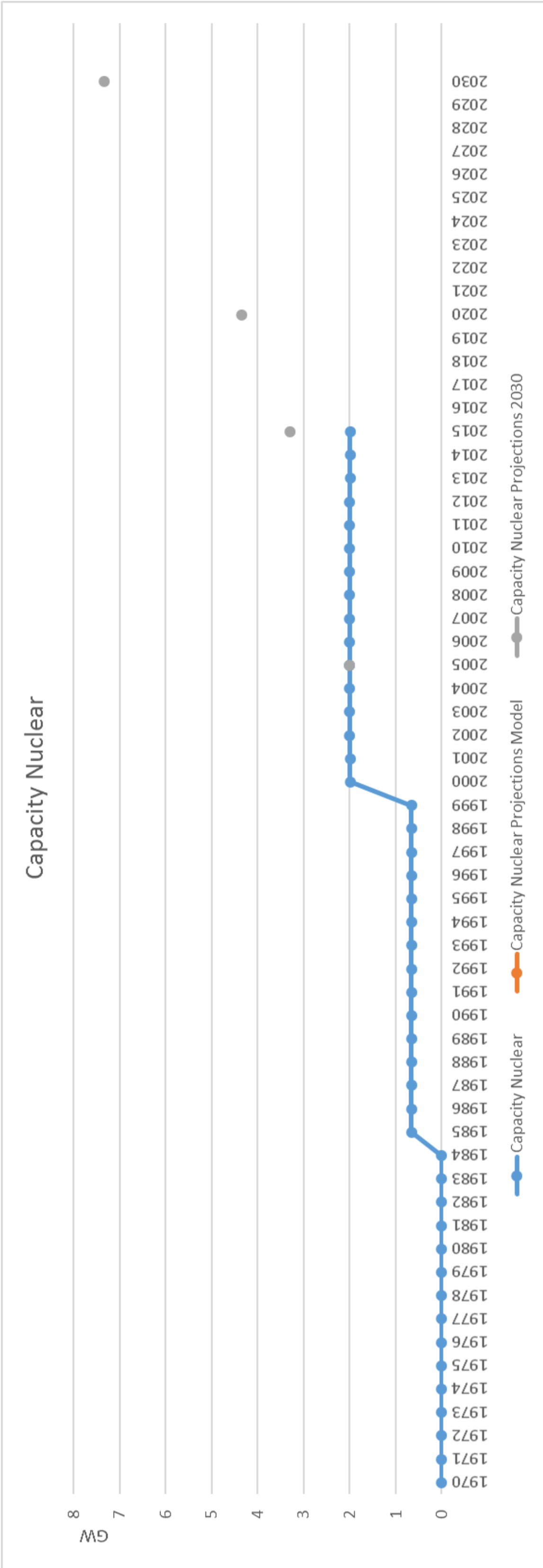


Figure 122: Projections for Nuclear Installed Capacity

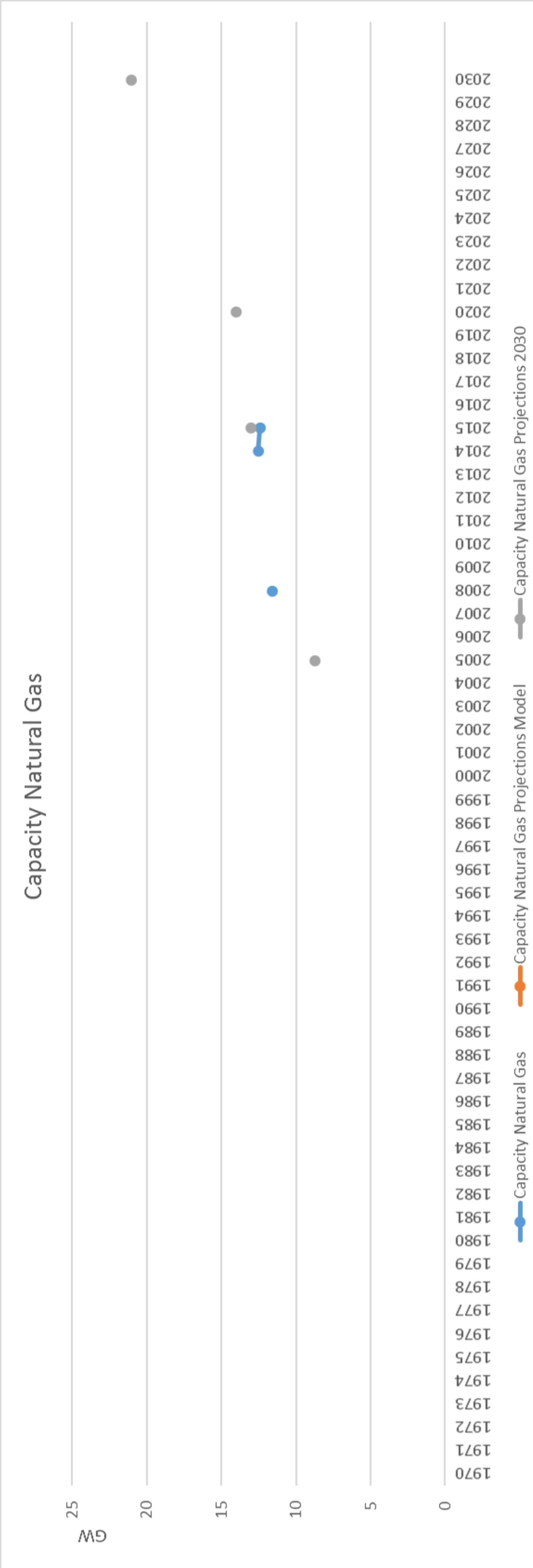


Figure 123: Projections for Installed Capacity Natural Gas

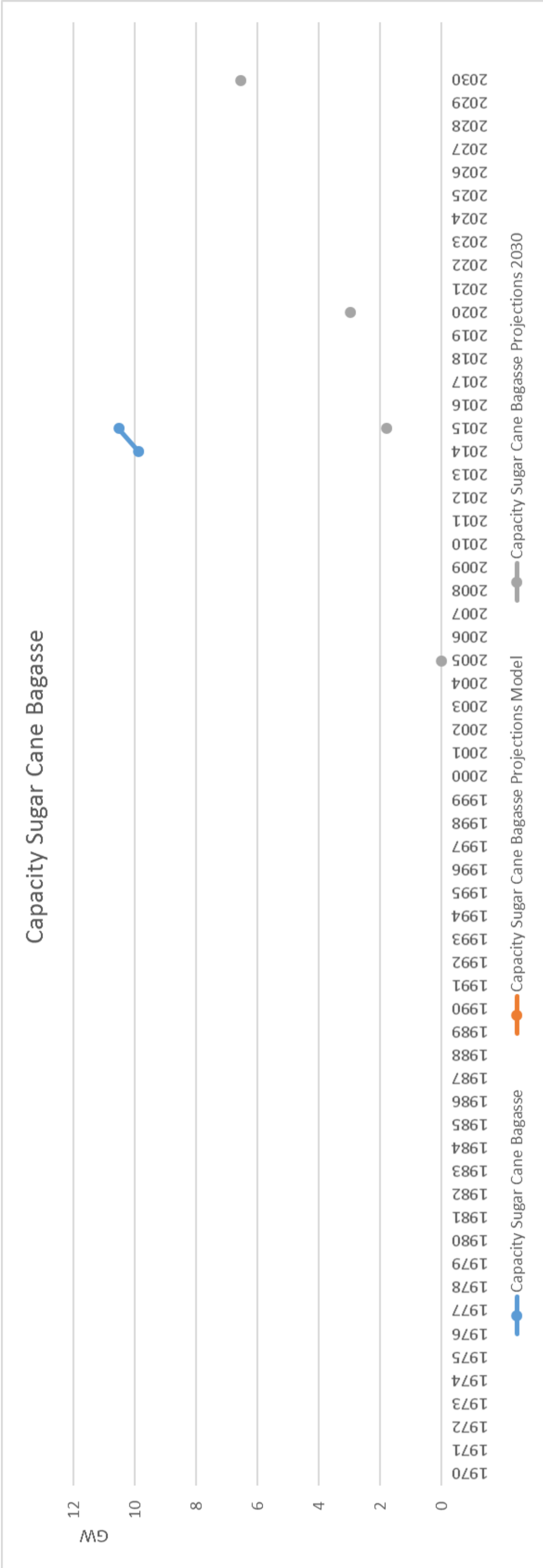


Figure 124: Projections for Installed Capacity Sugar Cane Bagasse

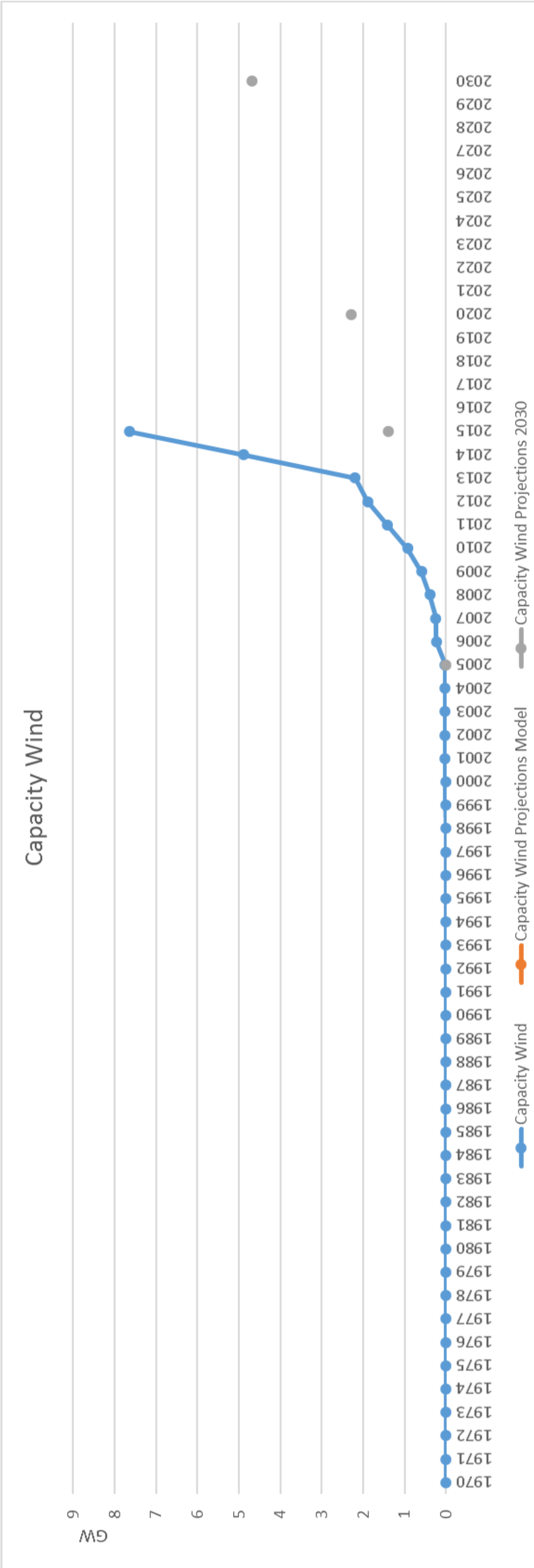


Figure 125: Projections for Installed Capacity Wind

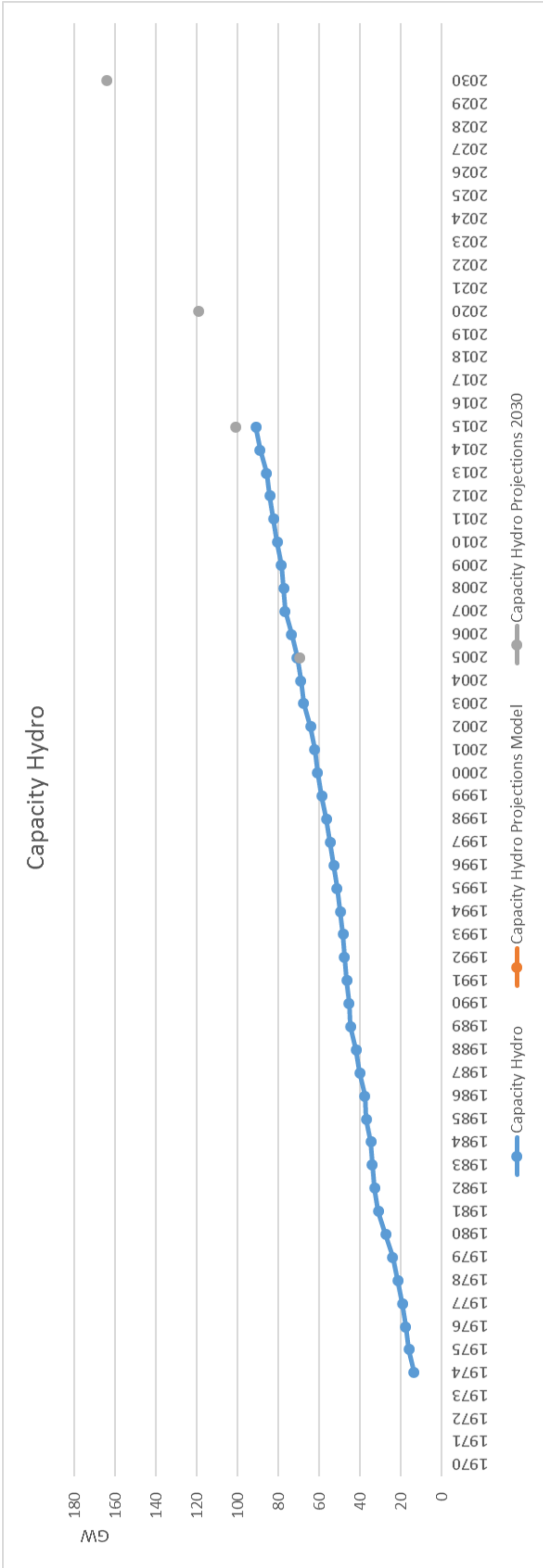


Figure 126: Projections for Installed Capacity Hydro